Pupillary Correlates of Fluctuations in Sustained Attention

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Abstract

■ The current study examined pupillary correlates of fluctuations and lapses of sustained attention. Participants performed a sustained attention task with either a varied ISI or a fixed ISI (fixed at 2 or 8 sec) while pupil responses were continuously recorded. The results indicated that performance was worse when the ISI was varied or fixed at 8 sec compared with when the ISI was fixed at 2 sec, suggesting that varied or long ISI conditions require greater intrinsic alertness compared with constant short ISIs. In terms of pupillary responses, the results demonstrated that slow responses (indicative of lapses) were associated with greater variability in tonic pupil diameter, smaller dilation responses during the ISI, and subsequently smaller dilation responses to stimulus onset. These results suggest that lapses of attention are associated with lower intrinsic alertness, resulting in a lowered intensity of attention to task-relevant stimuli. Following a lapse of attention, performance, tonic pupil diameter, and phasic pupillary responses, all increased, suggesting that attention was reoriented to the task. These results are consistent with the notion that pupillary responses track fluctuations in sustained attention. ■

INTRODUCTION

Our ability to maintain and sustain attention on goal-relevant tasks is fundamental for a number of everyday behaviors. This sustained attention (or vigilant attention) ability is thought to be a core aspect of attention control abilities that is distinct from our ability to select and divide our attention (Robertson & O'Connell, 2010; Sturm & Willmes, 2001; van Zomeren & Brouwer, 1994; Posner & Petersen, 1990). This sustained attention ability refers to attention control processes that are needed to maintain attention and engagement on task over time on relatively monotonous tasks. In particular, Robertson, Manly, Andrade, Baddeley, and Yiend (1997) suggest that sustained attention is "the ability to self-sustain mindful, conscious processing of stimuli whose repetitive, non-arousing qualities, would otherwise lead to habituation and distraction by other stimuli" (p. 747). A great deal of research suggests that sustaining attention on task is a difficult and effortful process not only for long duration tasks but also for the continuous allocation of attention over just a few seconds (Langner & Eickhoff, 2013; Parasuraman, Warm, & See, 1998; Posner, 1978).

A key aspect of sustained attention is the notion that attention fluctuates leading to variability in task performance. In particular, sustained attention fluctuates due to changes in energetic factors, such as motivation (e.g., intrinsic motivation to do well, extrinsic motivators such as incentives), arousal (e.g., circadian rhythm, sleep deprivation), and alertness. Alertness refers to the overall readiness to respond to external information. Alertness can be subdivided into phasic alertness (short-term readiness following a warning signal), tonic alertness (slow changing readiness linked to circadian rhythm and wakefulness), and intrinsic alertness (voluntary control of readiness over seconds to minutes in the absence of external cues; Sadaghiani & D'Esposito, 2015; Langner et al., 2012; Sturm & Willmes, 2001; van Zomeren & Brouwer, 1994). Thus, the intensity of attention that is allocated to a task is determined in part by current alertness levels with aspects of alertness being voluntarily controlled (intrinsic alertness). 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. These fluctuations in attention can lead to relatively minor changes in task engagement (and minor shifts in performance), or these fluctuations can lead to much large changes in task engagement (and large shifts in performance). These more extreme fluctuations can be conceptualized as lapses of attention whereby an individual briefly disengages from the current task.

A common means of examining fluctuations in sustained attention and alertness is to use simple RT tasks with variable ISIs. In these tasks, participants have to detect the occurrence of a target that typically occurs at an uncertain time point. As such, a key aspect of sustained attention tasks is the uncertainty of when the signal will occur. For example, in the psychomotor vigilance task (Lim & Dinges, 2008; Dinges & Powell, 1985), participants see a row of zeros and are told that when the numbers begin counting (like a stop watch) that they must press a key as fast as possible. Critically, the numbers

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This paper is part of a Special Focus deriving from a symposium at the 2017 annual meeting of Cognitive Neuroscience Society, entitled, "Fluctuations in Attention and Cognition."
University of Oregon

Journal of Cognitive Neuroscience 30:9, pp. 1241–1253
doi:10.1162/jocn_a_01251

begin counting anywhere from 2 to 10 sec after they appear. Thus, participants must maintain focused attention on the stimulus and maintain a high level of preparation to rapidly detect the occurrence of the signal and press the corresponding key once the signal occurs. As noted above, this preparatory maintenance process is thought to be effortful requiring a great deal of intrinsic alertness (Steinborn, Langner, & Huestegge, 2017; Langner & Eickhoff, 2013; Jennings & van der Molen, 2005; Woodrow, 1914). Indeed, Posner and Boies (1971) suggested that the "foreperiod of a reaction time task may be considered as a miniature vigilance situation where alertness must be developed rapidly and maintained over a relatively brief interval" (p. 391). Any lapse of attention, whereby attention is not adequately sustained and focused on the stimulus, should result in a longer than normal RT. A fixed temporal structure in which the stimulus always occurs at the same time (constant ISI), however, requires less focused attention and typically results in better overall performance on sustained attention tasks (Langner & Eickhoff, 2013; Shaw, Finomore, Warm, & Matthews, 2012). For example, Lisper and Törnros (1974) found a larger time-on-task effect (increase in RT as a function of time on task) with variable ISIs (4–11 sec) compared with a constant ISI (7.5 sec). Rather than needing to maintain attention throughout the entire interval, participants can ramp up attention in line with the occurrence of the stimulus (based on their time estimation abilities). As noted by Shaw et al. (2012), this should allow participants to take "task-contingent" time-outs and take breaks from sustaining attention (Langner, Willmes, Chatterjee, Eickhoff, & Sturm, 2010), thereby reducing the demands on sustained attention somewhat. Thus, a critical aspect of sustained attention is the ability to maintain a preparatory state of readiness over uncertain intervals. Fluctuations in intrinsic alertness then should be translated into performance fluctuations.

A great deal of research suggests that sustained attention is linked with a predominantly right lateralized cortical network that includes the frontal-parietal network, the salience network, and the default mode network (Fortenbaugh, DeGutis, & Esterman, 2017; Sadaghiani & D'Esposito, 2015; Langner & Eickhoff, 2013; Robertson & O'Connell, 2010; Sturm & Willmes, 2001; Parasuraman et al., 1998; Posner & Petersen, 1990). Collectively, this system is important for maintaining arousal and attention on task-relevant stimuli and for reorienting attention back to task-relevant stimuli following errors or lapses of attention. For example, Weissman, Roberts, Visscher, and Woldorff (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 responses were associated with lower activation in several areas thought to be associated with sustained attention. Specifically, Weissman et al. found that the slowest RTs were associated with reduced activity in the inferior frontal gyrus, the middle frontal gyrus, and the ACC before the onset of the stimulus. Weissman et al. argued that this reduced activity reflected a lapse of attention whereby participants were focusing on internal thoughts rather than the external stimulus before the onset of the trial. Weissman et al. (2006) also found that the slowest RTs were associated with reduced activity in sensory processing areas of the occipital cortex, suggesting that lapses of attention can lead to potentially lower quality perceptual representations. Weissman et al. further found that the slowest RTs were related to increased activity in areas of the default mode network. Weissman et al. (2006) argued that this increased activity reflected task-irrelevant thoughts (such as daydreaming), which lead to a lapse of attention and a subsequent decrement in goal-directed behavior. Furthermore, Weissman et al. found that right inferior frontal gyrus and right temporal-parietal junction predicted better performance on trials following slow RTs suggesting that these areas are important for reorienting attention following a lapse (see also Langner & Eickhoff, 2013). Similarly, using the psychomotor vigilance task, Drummond et al. (2005) found that the fastest RTs were associated with right frontal parietal regions, whereas the slowest RTs were associated with areas of the default mode network and suggested that this increased activity reflected instances of task disengagement and lapses of attention. Collectively, these results suggest that the slowest responses seem to provide an index of lapses of attention, which are related to reduced activity in sustained attention regions and increased activity in the default mode network regions, which lead to decrements in goal-directed behavior (although this latter finding is not always the case; see Fortenbaugh et al., 2017).

Examining EEG, O'Connell et al. (2009) found that lapses of attention (detection failures) were preceded by increased alpha band activity 20 sec before a lapse, and this was followed by decreased frontal P3 and contingent negative variation. Similarly, Padilla, Wood, Hale, and Knight (2006) found that lapses of attention were preceded by reduced contingent negative variation and reduced ERPs during visual processing. Furthermore, Padilla et al. found that ERPs increased following a lapse of attention suggesting that attention was reoriented to the task following an error. Consistent with fMRI results, this suggests that lapses of attention are typically preceded by reduced sustained attention activity, followed by increased sustained attention activity indicative of a reorientation of attention.

In addition to cortical areas, the locus coeruleus norepinephrine (LC-NE) system is also thought to be important for sustaining attention and alertness (Robertson & O'Connell, 2010; Samuels & Szabadi, 2008; Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Parasuraman et al., 1998; Posner & Petersen, 1990). Recent research suggests that the LC-NE is important for modulating pFC representations based on attentional control demands (Cohen, Aston-Jones, & Gilzenrat, 2004). In particular, the LC-NE system is important for determining arousal state and attentional interest. Within the LC-NE system, neurons demonstrate two modes of firing: tonic and phasic. Tonic activity refers to the overall baseline activity, and phasic activity refers to the brief increase in firing rate associated with salient stimuli. It is assumed that when tonic LC activity is low (hypoactive mode), alertness and the intensity of attention to task-relevant stimuli are low, leading to poor behavioral performance and little to no phasic LC activity in response to task-relevant stimuli. As tonic LC activity increases to an intermediate range (phasic mode), alertness and the intensity of attention increase, resulting in attention becoming more focused on task-relevant stimuli; LC phasic activity increases for target stimuli; and behavioral performance is optimal. However, as tonic LC activity increases further, the individual experiences a more distractible attentional state (lowered intensity of attention) leading to task disengagement, lowered LC phasic activity, and a reduction in behavioral performance. Collectively, this research suggests that the LC-NE system exhibits fluctuations between these various modes/states during simple attentional tasks, and these fluctuations are linked to fluctuations in behavioral performance and lapses of attention (Smith & Nutt, 1996).

One means of tracking fluctuations and lapses in attention is pupillometry. Prior research has shown 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. Furthermore, recent research has also suggested that pupil dilations are indirectly related to the functioning of the LC-NE system (Joshi, Li, Kalwani, & Gold, 2016; Reimer et al., 2016; McGinley, David, & McCormick, 2015; Varazzani, San-Galli, Gilardeau, & Bouret, 2015; Alnæs et al., 2014; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Samuels & Szabadi, 2008; Aston-Jones & Cohen, 2005). Prior research suggests that pupillometry can be important for the detection of lapses of attention. For example, examining errors on very small set sizes in a working memory task (thought to be due to lapses of attention), Unsworth and Robison (2015) found that errors were associated with much smaller than normal pretrial (tonic) baseline pupil diameters than correct trials. Furthermore, in an extended sustained attention task, Kristjansson, Stern, Brown, and Rohrbaugh (2009) found that baseline pupil diameter was much smaller on trials preceding very slow RTs (indicative of lapses of attention) compared with trials where RT was close to the mean. Kristjansson et al. suggested that fluctuations in alertness resulted in variable RTs and that baseline pupil diameter provides an index of changes in alertness. Similarly, Unsworth and Robison (2016) found that lapses of attention (slow RTs) were preceded by larger than normal baseline pupil diameters (see also Konishi, Brown, Battaglini, & Smallwood, 2017). More recently, van den Brink, Murphy, and Nieuwenhuis (2016) found that both large and small baseline pupil diameter, along with fluctuations in pupil diameter, were associated with lapses of attention. Likewise in a large-scale individual differences study, Unsworth and Robison (2017a) found that fluctuations in both baseline pupil diameter and phasic pupillary responses were related to lowered attention control and increased RT variability. Collectively, these results suggest that pupillary responses (tonic and phasic) can be informative for examining fluctuations and lapses of attention linked to changes in alertness and the intensity of attention that are theoretically associated with fluctuations in LC-NE functioning.

The Current Study

Although prior research has suggested an encouraging link between pupillary responses and lapses of attention, much more work remains to be done to examine how well pupillary responses track lapses of attention and to gain further insights into potential causes of lapses of attention. Thus, the aim of the current study was to examine pupillary correlates of fluctuations of attention during a sustained attention task. In particular, we were interested in examining pupillary signatures of lapses of sustained attention. Participants performed a variant of the psychomotor vigilance task shown in Figure 1. In this task, participants are first presented with a row of fixation crosses in the middle of the screen for 2000 msec. Here pretrial baseline pupil diameter is measured. Next, participants are presented with a row of zeros in the center of the screen, and after a variable ISI, the zeros begin to count. The participants' task is to press the spacebar as quickly as possible once the numbers start counting. Theoretically, it is assumed that intrinsic alertness and the intensity of attention fluctuate both within and between trials. This has an impact on preparatory processes in which you need to energize and activate the task goal and maintain the task goal in a ready state while waiting for the stimulus to occur. When intrinsic alertness is high, preparatory processes are engaged such that the task goal is activated and maintained during the ISI so that when the numbers begin counting there is a fast RT and a large phasic pupillary response (intensity of attention is high). However, when intrinsic alertness is low, preparatory processes are not fully engaged, leading to weakened task goal activation and/or an inability to sustain the task goal over the interval. This should result in a longer than normal RT and a reduced phasic response.

Similar to prior neuroimaging studies, to examine these notions we examined differences between fast and slow responses. Specifically, we compared the fastest 20% of trials to the slowest 20% of trials. First, we examined potential differences in tonic/pretrial baseline pupil diameter for fast and slow responses. As noted above, some studies have found that slow RTs are preceded by smaller than normal baseline pupil diameters, larger than normal

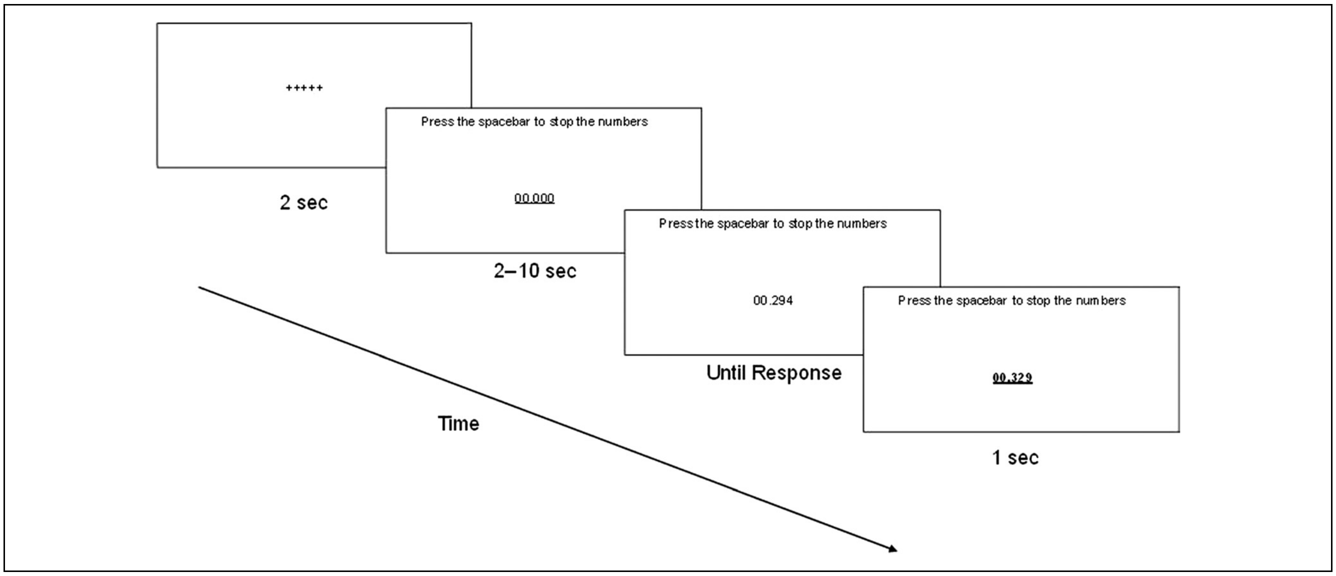


Figure 1. Schematic of the psychomotor vigilance task.

baseline pupil diameters, or both. Thus, we examined whether pretrial baseline pupil diameter differentiated fast and slow responses. Furthermore, given discrepancies across studies, we also examined variability in pretrial baseline pupil diameter as a potential differentiator of fast and slow responses. That is, perhaps rather than smaller or larger pupils, slow responses are differentiated from fast responses by overall differences in trial-to-trial variability in pupil diameter with lapses of attention being associated with greater variability (see Unsworth & Robison, 2017a).

Second, we examined potential differences between fast and slow responses during the ISI. As noted above, when intrinsic alertness is high, preparatory processes are fully engaged, and these processes should peak right before the expected occurrence of the stimulus (especially when the ISI is constant). Indeed, prior pupillometry studies have found that, with constant ISI (foreperiods), 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 (Jennings, van der Molen, & Steinhauer, 1998; van der Molen, Boomsma, Jennings, & Nieuwboer, 1989; Richer & Beatty, 1987; Richer, Silverman, & Beatty, 1983; Bradshaw, 1968, 1969). However, it is not known how this differs for fast versus slow responses. If pupillary responses during the ISI track intrinsic alertness, then there are three possibilities distinguishing fast from slow responses. (1) It is possible that there is an overall main effect such that fast trials are associated with greater pupil dilation than slow trials and this does not change over the course of the ISI. This would indicate that fast trials are associated with greater intensity of attention overall compared with slow trials. (2) It is possible that fast and slow trials do not differ at the onset of the ISI, but that fast trials are associated with an increase in pupil dilation during the ISI peaking right before stimulus onset indicating that intrinsic alertness increases throughout the ISI. Slow trials, however, might be associated with no change in pupil dilation during the ISI, indicating no change in intrinsic alertness across the ISI. (3) It is possible that fast and slow trials do not differ at the onset of the ISI, but that slow trials are associated with a decrease in pupil dilation across the ISI, indicating that on those trials participants could not maintain attention during the ISI (i.e., a minivigilance decrement during the trial). By examining pupillary responses during the ISI for fast and slow responses, we should be able to examine how intrinsic alertness levels differ for lapse and nonlapse trials.

Third, we examined differences in phasic responses. Prior research has suggested that phasic responses are smaller when participants report mind wandering than when they report being on-task (Unsworth & Robison, 2016, 2017b; Grandchamp, Braboszcz, & Delorme, 2014; Mittner et al., 2014). Thus, as noted above, a similar result should be obtained when examining fast versus slow responses, with slow responses being associated with smaller phasic pupillary responses indicative of a lower intensity of attention.

Fourth, we examined behavioral and pupillary responses on the trial immediately following a lapse trial. As noted above, prior fMRI and EEG research has suggested that, following a lapse of attention (slow RT or error), attention is reoriented to the task leading to greater attention and performance on the next trial (Padilla et al., 2006; Weissman et al., 2006). Similarly, following a lapse in the current task (assuming one is aware of the lapse), we might expect that overall tonic pupil diameter increases indicating an increase in alertness and arousal. We might also expect an increase in phasic pupillary responses indicating an increase in the intensity of attention following a lapse, which should lead to a relatively fast response.

Another main goal of the current study was to examine how manipulations thought to influence intrinsic alertness (expectancy) influence lapses of attention and corresponding pupillary responses. As noted previously, with a varied ISI the demand on intrinsic alertness is high, given that it is not clear when the stimulus will occur. However, with a fixed ISI demands on intrinsic alertness should be lessened, given that participants can ramp up attention in line with the occurrence of the stimulus (based on their time estimation abilities). Furthermore, with a relatively short ISI, not only can participants anticipate when the stimulus will occur but fast pacing of the task should also promote more task engagement and fewer lapses of attention between trials. This notion is consistent with prior research on goal neglect, which suggests that task pacing influences goal maintenance abilities (De Jong, Berendsen, & Cools, 1999). For example, De Jong et al. reasoned that a fast paced task should keep attention tightly focused on the task goal, thereby preventing goal neglect. Slow-paced tasks, however, should induce more goal neglect, as participants would have ample time between trials to think about things unrelated to the task (i.e., mind wander), and thus, the goal would not be as actively maintained. This suggests that, in a fast-paced task, attention should be tightly focused on the task goal resulting in better performance and fewer lapses of attention.

To examine these issues, participants performed a variant of the psychomotor vigilance task described previously. Participants performed the psychomotor vigilance task with either a varied ISI (2–10 sec) or a fixed ISI. Within the fixed ISI conditions, some participants had an ISI of 2 sec, whereas other participants had an ISI of 8 sec. In this way, we manipulated not only the expectancy of when the stimulus would occur but also task pacing. RTs and pupillary responses were the main dependent measures of interest.

METHODS

Participants

Participants were 117 individuals between the ages of 18 and 35 recruited from the subject pool at the University of Oregon. Each participant was tested individually in a laboratory session lasting approximately 1 hr. In the Varied condition there were 36 participants, in the Fixed 2 condition there were 39 participants, and in the Fixed 8 condition there were 42 participants. One participant was excluded from the Varied condition for having a mean RT greater than 3 *SD* from the mean. Note that the Fixed 2 and Fixed 8 conditions are from Unsworth and Robison (2017b), where we examined pupillary differences in attentional states based on thought probe responses. None of the current analyses were reported in the prior study. In addition, note that the Varied condition was initially run as a separate experiment, but given that the exact same task (except for different ISIs) was used, it was included in the current analyses. None of the data from the Varied condition have been reported previously.

Procedure

Participants were tested individually in a dimly lit room. After providing informed consent and after calibrating the eye tracker, participants performed a variant of the psychomotor vigilance task (Dinges & Powell, 1985). As shown in Figure 1, in this task participants were first presented with a row of five black fixation crosses in the middle of the screen on a white background for 2000 msec. Participants were then presented with a row of zeros in blue Arial font 24 (visual angle 1.21°) in the center of the screen. In the Varied condition, after a variable ISI (equally distributed from 2 to 10 sec in 500-msec increments) the zeros began to count in 17-msec intervals from 0 msec. In the Fixed 2 condition, the zeros always began counting after 2 sec. In the Fixed 8 condition, the zeros always began counting after 8 sec. The participants' task was to press the spacebar as quickly as possible once the numbers started counting. After pressing the spacebar, the RT was left on screen in red for 1 sec to provide feedback to the participants (shown in bold in Figure 1). Following feedback, a 500-msec blank screen was presented, and then either the next trial started or participants were presented with a thought probe. Participants performed 120 trials, and the experiment lasted approximately 30 min. Thirty thought probes were randomly presented after roughly 19% of the trials equally distributed across blocks. The thought probes asked participants if on the immediately preceding trial they were on-task, experiencing task-related interference, experiencing external distraction, intentionally mind wandering, unintentionally mind wandering, or mind blanking. Thought probe results from the fixed ISI conditions were reported in Unsworth and Robison (2017b), and none of the thought probe results are examined in the current study.

Eye Tracking

Pupil diameter was continuously recorded binocularly at 120 Hz using a Tobii T120 eye tracker. Participants were seated approximately 60 cm from the monitor with the use of chinrest. Stimuli were presented on the Tobii T120 eye tracker 17-in. monitor with 1024 × 768 screen resolution. Data from each participant's left eye were used. Missing data points due to blinks, off-screen fixations, and/or eye tracker 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 (2000 msec).

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 msec time windows following the appearance of the numbers for each trial. Phasic responses to the onset of the stimulus were corrected by subtracting out the last 200 msec of the ISI and locked to when the numbers began counting on a trial-by-trial basis for each participant. To examine the time course of the phasic pupillary responses, the pupil data were averaged into a series of 20 msec time windows following stimulus onset for each trial. The dependent measure in the phasic pupillary response analyses was the peak task-evoked response given a clear peak is present in the waveform. Specifically, the peak was defined as the maximal dilation following stimulus onset for each trial and each participant. The peak dilation typically occurred between 550 and 750 msec poststimulus in the psychomotor vigilance task (Unsworth & Robison, 2016). The last 200 msec of the ISI was then subtracted from the peak dilation for each trial, and each participant to get the peak task-evoked response for that trial (Beatty & Lucero-Wagoner, 2000).

RESULTS

Behavioral Results

First, we examined differences in RT (the full distributions) as a function of condition. Specifically, each individual's RTs were rank-ordered from fastest to slowest. Next, these rank-ordered responses were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants to examine differences in the distributions across conditions. There was a main effect of Condition, $F(2, 113) = 24.42$, $MSE = 10307.81$, $p < .001$, partial $\eta^2 = .30$, suggesting that the Fixed 2 condition was faster (both *p*s < .001, Bonferroni-corrected post hoc comparisons) than both the Varied and Fixed 8 conditions (which did not differ from one another $p = .90$). There was also a main effect of Quintile as would be expected, $F(4, 452) = 485.03$, $MSE = 1203.35$, $p < .001$, partial $\eta^2 = .81$. Importantly, there was also a Condition × Quintile interaction, $F(8, 452) = 2.64$, $MSE = 1203.35$, $p = .008$, partial $\eta^2 = .05$. As shown in Figure 2A, the Varied and Fixed 8 conditions did not differ from one another. The Fixed 2 condition was associated with an overall shift in the distribution (shifted toward faster responses), with most differences between conditions occurring at the fastest bin. Thus, having the stimuli always occur at 2 sec resulted in overall very fast responses. Indeed, examining differences in the number of responses 500 msec or greater (what is typically considered as a lapse in the psychomotor vigilance task; Lim & Dinges, 2008) suggested a difference in the number of lapses as a function of condition, $F(2, 113) = 4.64$, $MSE = 51.15$, $p = .012$, partial $\eta^2 = .08$, with the Fixed 2 condition demonstrating fewer lapses ($M = 2.51$, $SD = 3.71$) than both the Varied ($M = 6.91$, $SD = 6.44$) and Fixed 8 conditions ($M = 6.69$, $SD = 9.68$; both *p*s < .03), which did not differ from one another ($p > .98$).[1]

Next we examined time-on-task effects. RTs were grouped into five blocks of 24 trials each. Consistent with prior research, a classic vigilance decrement was observed, such that as time on task increased so did RTs (see Figure 2B), $F(4, 452) = 18.82$, $MSE = 777.56$, $p < .001$, partial $\eta^2 = .14$. Importantly, there was also a Condition × Block interaction, $F(8, 452) = 7.43$, $MSE = 777.56$, $p < .001$, partial $\eta^2 = .12$. As shown in Figure 2B, the Varied and Fixed 8 conditions both demonstrated time-on-task effects, which were of the same magnitude. However, in the Fixed 2 condition, RTs did not increase with time on task. Collectively, these results suggest that having a fast fixed ISI (Fixed 2 condition) served to increase overall attention to the task resulting in faster overall performance, fewer lapses of attention, and no time-on-task effect.

Pupillary Results

Tonic Pupil Diameter

First, examining differences in average tonic (pretrial baseline) pupil diameter suggested that there were no differences across conditions, $F(2, 113) = .73$, $MSE = .07$, $p = .485$, partial $\eta^2 = .01$. Examining variability (coefficient of variation) in tonic pupil diameter, however, suggested differences across conditions, $F(2, 113) = 3.83$, $MSE = .001$, $p = .024$, partial $\eta^2 = .06$, with the Fixed 2 condition having less variability ($M = .06$, $SD = .02$) in tonic pupil diameter than the Fixed 8 condition ($M = .08$, $SD = .04$, $p = .021$), but not the Varied condition ($M = .07$, $SD = .02$, $p = .286$). The Fixed 8 and Varied conditions did not differ ($p > .98$).

Next, we examined differences in tonic pupil diameter between fast and slow responses as a function of condition. Fast responses consisted of the 20% fastest trials, and slow responses consisted of the 20% slowest trials. For these within-participant analyses, tonic pupil diameter was *z*-scored normalized within each participant to correct for individual differences in pupil diameter. The effect of response was not quite significant, $F(1, 113) = 3.40$, $MSE = .048$, $p = .068$, partial $\eta^2 = .03$. The interaction between Condition and Response was right at the level of conventional significance, $F(2, 113) = 3.09$, $MSE = .048$, $p = .049$, partial $\eta^2 = .05$. The interaction suggested that there were no differences between fast and slow responses in tonic pupil diameter in either the Varied condition (M diff $= -.04$, $SD = .28$, $p = .39$) or in the Fixed 8 condition (M diff $=.06$, $SD = .34$, $p = .24$). In the Fixed 2 condition, however, slow responses were associated with larger tonic pupil diameter than fast responses

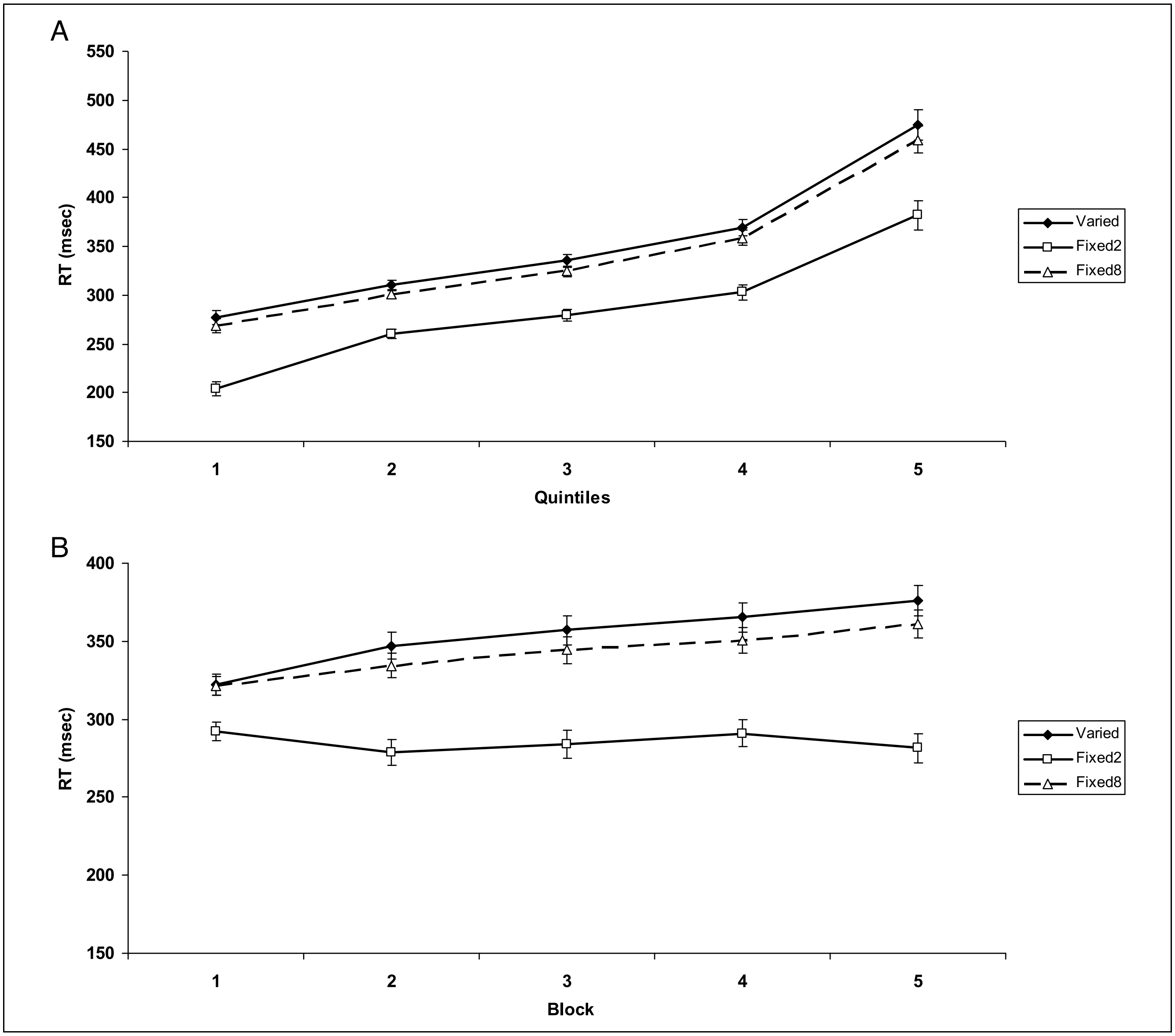


Figure 2. (A) Quintile plots as a function of condition. (B) Mean RT as a function of condition and block. Error bars reflect 1 *SEM*.

(*M* diff = .14, *SD* = .30, p = .007). Thus, there was inconsistent evidence that pretrial tonic pupil diameter provides an index of lapses of attention as indexed by slower than normal RTs.

Examining variability (coefficient of variation) in tonic pupil diameter for fast and slow responses suggested differences, $F(1, 113) = 12.37$, $MSE = .001$, $p = .001$, partial $\eta^2 = .10$, with slow responses being associated with more trial-to-trial variability in pupil diameter (*M* = .053, *SD* = .024) than fast responses (*M* = .048, *SD* = .020). Similar to the above analysis, there was a main effect of Condition, $F(2, 113) = 42.15$, $MSE = .001$, $p < .001$, partial $\eta^2 = .43$. The Response × Condition interaction was not quite significant, $F(2, 113) = 2.87$, $MSE = .001$, $p = .061$, partial $\eta^2 = .05$. Thus, consistent with some prior research, variability in tonic pupil diameter was associated with lapses of attention.

Phasic Pupillary Responses During the ISI

Our next set of analyses focused on pupillary responses during the ISI. As noted previously, examining pupillary responses during the ISI (particularly the fixed ISI conditions) should provide us with information on how intrinsic alertness and preparatory attention processes are engaged while waiting for the stimulus to occur and how this potentially differs for fast and slow responses. We examined the Fixed 2 and Fixed 8 conditions separately and examined pupillary phasic responses for each time bin for fast and slow responses, respectively. Note that we did not analyze the Varied condition because there were not enough fast and slow responses in each ISI for each participant. As noted above, 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 msec time windows following the appearance of the zeros for each trial.

First, examining the Fixed 2 condition suggested a main effect of Response, $F(1, 38) = 4.75$, $MSE = .007$, $p = .035$, partial $\eta^2 = .11$, in which phasic responses were larger for fast responses than for slow responses. There was a main effect of Time bin, $F(9, 342) = 8.90$, $MSE = .001$, $p < .001$, partial $\eta^2 = .19$, suggesting that the pupil tended to increase during the ISI. Importantly there was a significant Response × Time bin interaction, $F(9, 342) = 12.36$, $MSE = .001$, $p < .001$, partial $\eta^2 = .25$. As shown in Figure 3A, there were no differences in the pupillary response during the early part of the ISI. However, the pupillary response for fast responses increased before the onset of the stimulus consistent with prior research. For slow responses, however, there was no preparatory increase in the pupillary response. Thus, by the last time bin, there was a significant difference between fast and slow responses, $t(38) = 5.29$, $p < .001$, $d = .88$.

Examining the Fixed 8 condition suggested no main effect of Response, $F(1, 41) = .17$, $MSE = .023$, $p = .685$, partial $\eta^2 = .004$. There was a main effect of Time bin, $F(39, 1599) = 8.20$, $MSE = .003$, $p < .001$, partial $\eta^2 = .17$, suggesting that the pupil tended to decrease during the first part of the ISI but then increase in anticipation of the onset of the stimulus. Importantly, there was a significant Response × Time bin interaction, $F(39, 1599) = 2.52$, $MSE = .002$, $p < .001$, partial $\eta^2 = .06$. As shown in Figure 3B, slow responses demonstrated a larger increase in the pupillary response during the early part of the ISI. However, the pupillary response for fast responses increased

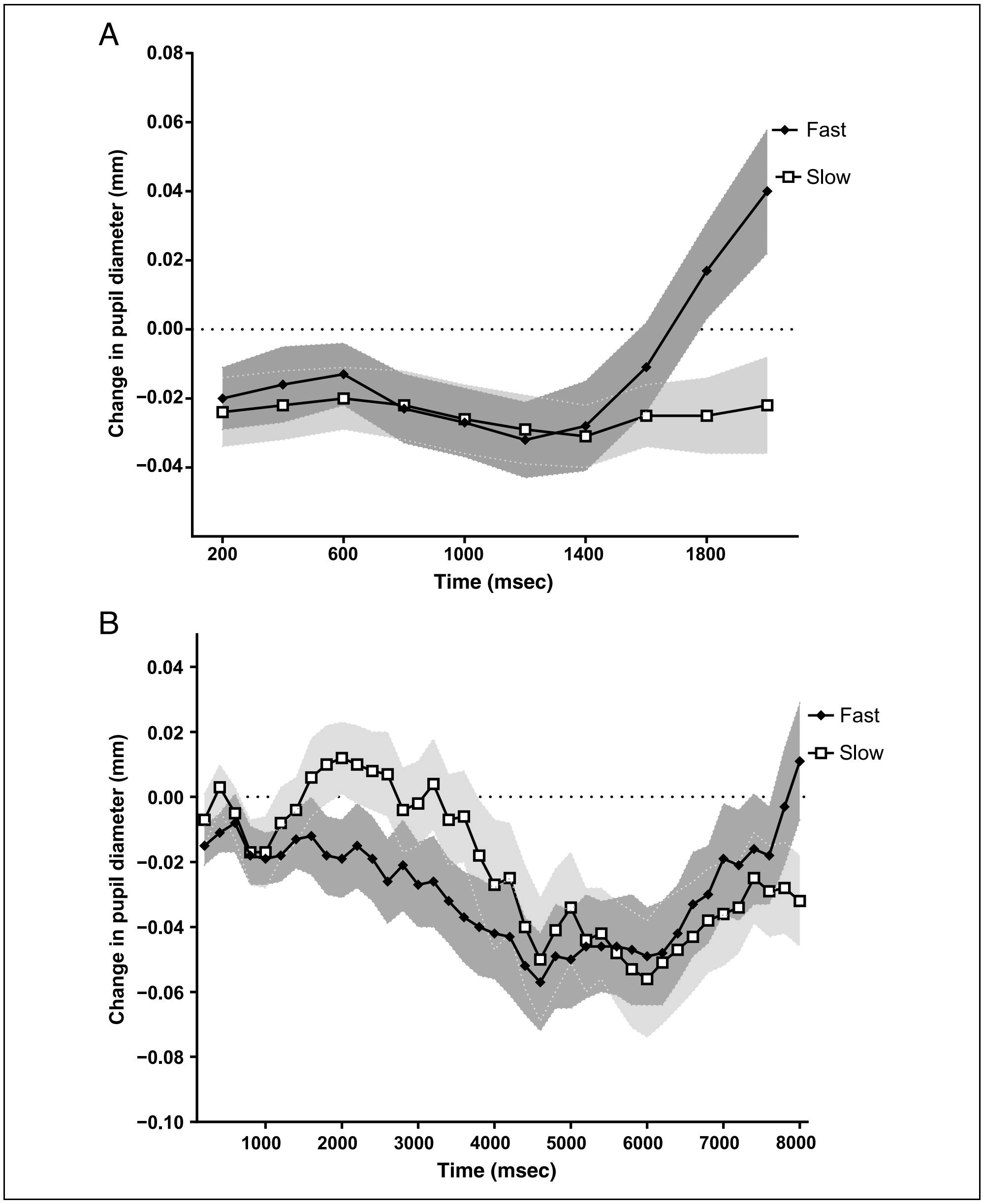


Figure 3. (A) Change in pupil diameter for fast and slow responses as a function of time during the ISI for the Fixed 2 condition. (B) Change in pupil diameter for fast and slow responses as a function of time during the ISI for the Fixed 8 condition. Shaded areas reflect 1 *SEM*.

more before the onset of the stimulus than the slow responses, with the fast responses demonstrating more dilation in the last time bin than the slow responses, $t(41) = 2.12$, $p = .04$, $d = .33$, similar to what was found in the Fixed 2 condition. Thus, fast responses were preceded by increases in intrinsic alertness, but lapses were associated with no change in intrinsic alertness (Fixed 2 condition) or a smaller change in intrinsic alertness (Fixed 8 condition).

Phasic Pupillary Responses to Stimulus Onset

Next, we examined differences in phasic pupillary responses to stimulus onset (i.e., when the numbers began counting). As noted above, phasic responses to the onset of the stimulus were corrected by subtracting out the last 200 msec of the ISI and locked to when the numbers began counting on a trial-by-trial basis for each participant. To examine the time course of the phasic pupillary responses, the pupil data were averaged into a series of 20 msec time windows following stimulus onset for each trial. The dependent measure in the phasic pupillary response analyses was the peak task-evoked response given a clear peak is present in the waveform. The waveforms are presented for visualization purposes. First differences in overall phasic responses as a function of Condition were examined. There was a significant effect of condition, $F(2, 113) = 3.37$, $MSE = .003$, $p = .038$, partial $\eta^2 = .06$, with the Fixed 2 condition demonstrating a larger phasic response ($M = .117$, $SD = .057$) than the Varied condition ($M = .087$, $SD = .042$, $p = .046$), but not the Fixed 8 condition ($M = .094$, $SD = .054$, $p = .17$). The Varied and Fixed 8 conditions did not differ ($p > .98$).

Next, we examined differences in phasic pupillary responses between fast and slow responses as a function of condition. There was a main effect of Response, $F(1, 113) = 19.89$, $MSE = .003$, $p < .001$, partial $\eta^2 = .15$, suggesting that fast responses were associated with larger phasic responses than slow responses. The main effect of Condition was not quite significant, $F(1, 113) = 2.95$, $MSE = .006$, $p = .057$, partial $\eta^2 = .05$. Finally, the interaction between response and condition was not significant, $F(2, 113) = 1.63$, $MSE = .003$, $p = .201$, partial $\eta^2 = .03$. Thus, as shown in Figure 4, fast responses were associated with larger phasic pupillary responses than slow responses, suggesting that lapses of attention were associated with a lower intensity of attention to the stimulus.

Pupillary Responses Following Slow RTs

Our final set of analyses examined what happens on trials immediately following a slow (lapse) trial. First examining RTs, we compared RTs for the slow trial and the trial immediately following the slow RT. The results suggested that, following a slow RT, RTs tend to decrease by about 98 msec ($SD = 49$), $F(1, 113) = 474.68$, $MSE = 1164.62$, $p < .001$, partial $\eta^2 = .81$, consistent with prior research (Bertelson & Jaffe, 1963). This did not interact with condition, $F(2, 113) = 2.24$, $MSE = 1164.62$, $p = .111$, partial $\eta^2 = .04$, suggesting that participants reengaged after a lapse in all conditions. Of course because we are specifically looking at trials following a very slow trial, it is very likely that these results simply reflect regression to the mean. In fact, examining trials following a lapse and corresponding mean RTs from similar times during the task suggest no difference in RTs ($p = .68$).

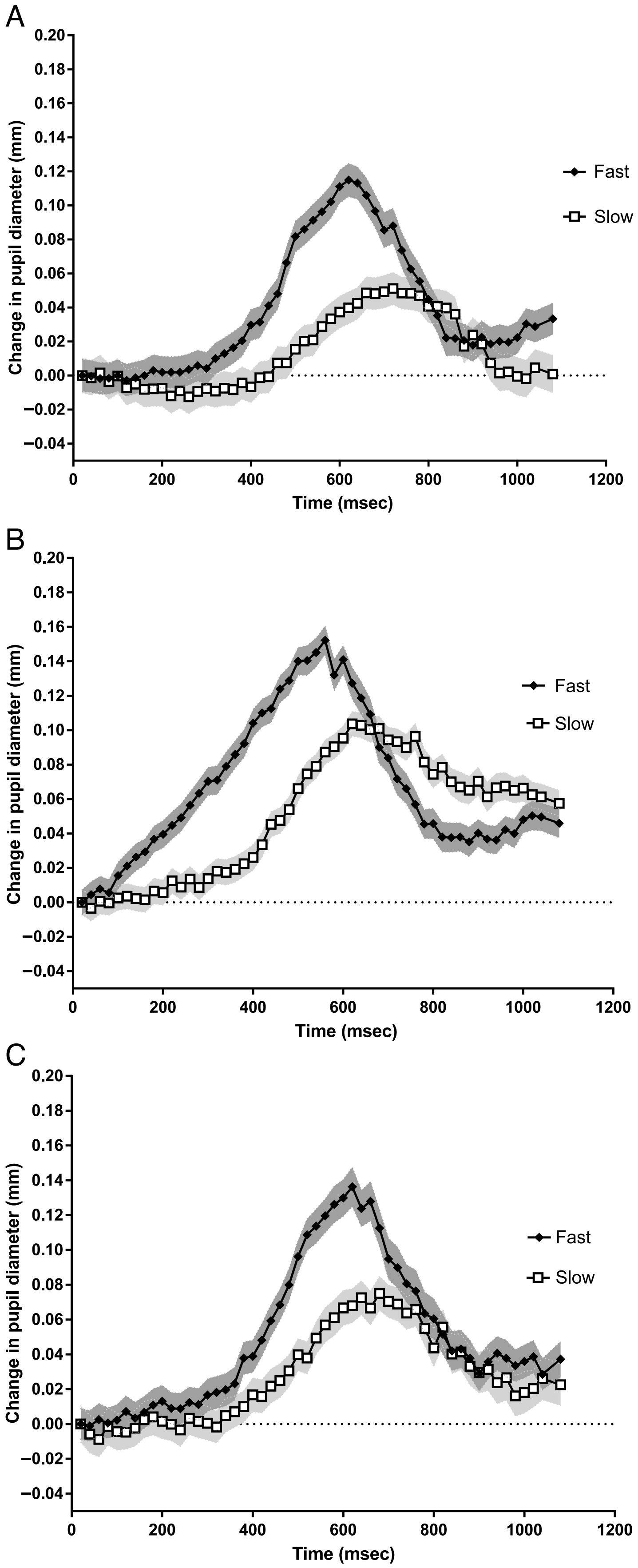
Next, examining tonic pupil diameter, there was no overall main effect, $F(1, 113) = .014$, $MSE = .039$, $p = .907$, partial $\eta^2 = .00$. However, there was an interaction with Condition, $F(2, 113) = 6.35$, $MSE = .039$, $p = .002$, partial $\eta^2 = .10$, suggesting that, following a slow response, tonic pupil diameter tended to increase in both the Varied ($M = .064$, $SD = .28$) and Fixed 8 conditions ($M = .060$, $SD = .30$). In the Fixed 2 condition, however, following a slow response tonic pupil diameter tended to decrease on the next trial ($M = -.133$, $SD = .25$).

Finally, examining phasic pupillary responses to stimulus onset suggested that, following a slow response, phasic pupillary responses tended to increase by about 0.01 mm ($SD = .05$), $F(1, 113) = 4.00$, $MSE = .001$, $p = .048$, partial $\eta^2 = .03$. The interaction with Condition did not quite reach conventional levels of significance, $F(2, 113) = 2.48$, $MSE = .001$, $p = .088$, partial $\eta^2 = .04$. Similar to the RT results, it is possible that these results are due to regression to the mean.

DISCUSSION

In the current study, we examined behavioral and pupillary correlates of fluctuations in sustained attention. Participants performed a sustained attention task in which ISIs were varied or fixed. The results suggested that performance was worse (slower RTs, greater RT variability, more lapses of attention, and larger time-on-task effects) when the ISI was varied or fixed at 8 sec compared with when the ISI was fixed at 2 sec. These results are broadly consistent with prior research suggesting that simple RT tasks with a varied ISIs require greater intrinsic alertness compared with when ISIs are fixed (Langner & Eickhoff, 2013; Jennings & van der Molen, 2005). However, the results also suggest that the length of the ISI matters. Specifically, in the current study when the ISI was fixed at 8 sec, the results were nearly identical to the varied condition, suggesting that this longer ISI was functionally similar to the Varied condition. That is, both required a great deal of intrinsic alertness during the ISI for successful performance. When the ISI was fixed at 2 sec, however, the demand on intrinsic alertness was lower, and less attention was needed to maintain readiness over the shorter fixed interval resulting in fast overall performance. Furthermore, we argue that the Fixed 2 ISI condition not only required less intrinsic alertness during

Figure 4. (A) Change in pupil diameter for fast and slow responses as a function of time after stimulus onset for the Varied condition. (B) Change in pupil diameter for fast and slow responses as a function of time after stimulus onset for the Fixed 2 condition. (C) Change in pupil diameter for fast and slow responses as a function of time after stimulus onset for the Fixed 8 condition. Shaded areas reflect 1 *SEM*.



the trial but also required less attention between trials. That is, given the fast task pacing in the Fixed 2 ISI condition, the task goal was constantly maintained (i.e., there was less chance of mind wandering and goal neglect to occur) between trials, keeping the participant engaged in the task (i.e., De Jong et al., 1999). This resulted in not only fewer lapses of attention but also no time-on-task effects. Thus, situations that promoted more task engagement resulted in fewer demands on intrinsic alertness and goal maintenance processes, resulting in fewer fluctuations in attention. Situations that required a great deal of intrinsic alertness and goal maintenance, however, were more prone to fluctuations in attention resulting in worse overall performance.

The pupillary results were largely consistent with the behavioral results. There were fewer fluctuations in tonic pupil diameter in the Fixed 2 condition compared with the Varied and Fixed 8 conditions. Overall phasic pupillary responses to stimulus onset were larger for the Fixed 2 condition, suggesting that the intensity of attention was greater in that condition. Furthermore, examining differences between fast and slow responses (our index of lapses of attention) suggested that there were several pupillary signatures of lapses of attention. For example, consistent with prior research, variability in tonic pupil diameter was associated with lapses of attention (Unsworth & Robison, 2017a). At the same time, overall tonic baseline pupil diameter did not necessarily differentiate fast and slow responses, adding to the inconsistent nature of tonic pupil diameter as an index of lapses of attention (Konishi et al., 2017; Unsworth & Robison, 2016; van den Brink et al., 2016; Kristjansson et al., 2009). However, during the ISI fast responses were associated with greater dilation right before the onset of the stimulus than slow responses. In terms of the possibilities mentioned in the Introduction, the results are most consistent with the second possibility suggesting that lapse trials are associated with lowered levels of intrinsic alertness. That is, when attention is not fully focused on the task at hand, the ability to voluntarily increase readiness and alertness and properly engage and sustain preparatory processes is lessened resulting in a longer than normal RT. Furthermore, this reduction in intrinsic alertness was associated with a smaller than normal phasic pupillary response to stimulus onset. As shown in Figure 4, in all conditions lapse trials were associated with a much smaller phasic response than fast trials, suggesting that the intensity of attention to the stimulus was much weaker on slow trials than fast trials. Together, the smaller dilation responses during both the ISIs and to the stimulus associated with slow trials provide a nice consistent signature of lapses of attention and provide information on what is occurring during lapse trials. In particular, these results suggest that lapses of attention are associated with lower intrinsic alertness in which the current task goal is only weakly activated (making goal maintenance difficult), resulting in a lowered intensity of attention to task-relevant stimuli. Given the importance of preventing lapses of attention in a number of everyday situations, these signatures of lapses can potentially be used to detect and correct lapses of attention during situations that demand sustained attention. Future research is needed to validate potential techniques for using these pupillary signatures to catch lapses in real time.

The current results also provide interesting information on what happens following a lapse of attention. Specifically, we found that following a lapse of attention performance increased (i.e., RTs decreased), tonic pupil diameter tended to increase indicating that tonic arousal was increased, and phasic pupillary responses to the stimulus were increased suggesting that the intensity of attention was increased. Consistent with prior research, the current results suggest that following a lapse, attention is reoriented to the task, intrinsic alertness is increased, and the overall intensity of attention to task-relevant stimuli is increased (Langner & Eickhoff, 2013; Padilla et al., 2006; Weissman et al., 2006). At the same time, some of these results could be due to regression to the mean, and it is important for future research to further examine what happens after a lapse of attention by examining various different indicators of lapses to see if similar patterns of results are found.

Collectively, the current results suggest that, on trials associated with very fast responses, the pupil demonstrates increased dilation both before and during stimulus onset indicating greater intrinsic alertness and intensity of attention. On trials associated with very slow responses, however, the pupil demonstrates a much weaker dilatory response both before and during stimulus onset, indicating a reduction in intrinsic alertness and the intensity of attention. These results are broadly consistent with the notion that pupillary responses provide a consistent means of tracking fluctuations in intrinsic alertness and attention (linked to LC-NE and cortical sustained attention network functioning) during tasks that demand a great deal of sustained attention for optimal performance.

Acknowledgments

This research was supported by the Office of Naval Research, grant N00014-15-1-2790.

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Note

1. Note that some of these differences were likely due to anticipatory responses that occurred in the Fixed 2 condition. Specifically, examining false alarms (i.e., hitting the spacebar before the numbers started counting) suggested a main effect of Condition, $F(2, 113) = 4.63$, $MSE = 3.61$, $p = .012$, partial $\eta^2 = .08$, with the Fixed 2 condition demonstrating more false alarms ($M = 1.51$, $SD = 2.47$) than both the Varied ($M = .38$, $SD = .94$) and Fixed 8 conditions ($M = .37$, $SD = 2.03$). To ensure that the results were not simply due to anticipatory

responses, we excluded any RTs faster than 100 msec in each condition. The overall results were nearly identical to those reported.

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