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Individual differences in baseline oculometrics: Examining variation in baseline pupil diameter, spontaneous eye blink rate, and fixation stability

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Abstract

Individual differences in baseline oculometrics (baseline pupil diameter, spontaneous eye blink rate, fixation stability), and their relation with cognitive abilities, personality traits, and self-report assessments were examined. Participants performed a baseline eye measure in which they were instructed to stare at a fixation point onscreen for 5 min. Following the baseline eye measure, participants completed a questionnaire asking what they were thinking about during the baseline eye measure. Participants also completed various cognitive ability measures assessing working memory capacity, attention control, and off-task thinking. Finally, participants completed a number of questionnaires assessing personality, Attention Deficit/Hyperactivity Disorder symptomology, mind wandering, and morningness-eveningness. Overall, the vast majority of correlations with the baseline eye measures were weak and nonsignificant, suggesting that these associations may not be very robust. The results also demonstrated the importance of examining what participants are thinking about during the baseline measure. These results add to the growing body of findings suggesting inconsistent relations between different baseline eye measures and various individual differences constructs.

Keywords Cognitive control · Norephinephrine · Dopamine · Working memory

Introduction

A great deal of prior research suggests that eye measures extracted at baseline, such as baseline pupil diameter, spontaneous eye blink rate, and fixation stability, provide important indicators of individual differences in cognitive abilities and personality traits potentially linked to different neuromodulatory systems. For example, it is thought that baseline pupil diameter is linked to functioning of the locus coeruleus norepinephrine system and spontaneous eye blink rate is associated with dopamine. In the current paper we examine whether variation in these baseline oculometrics are associated with individual differences in cognitive abilities and personality traits as predicted by prior theory.

Baseline pupil diameter

Much prior research has examined pupil dilation in response to task demands (e.g., phasic pupillary responses) and suggested that these task-evoked pupillary responses are indicative of mental effort and the intensity of attention (Beatty & Lucero-Wagoner, 2000). At the same time, research has examined how changes in tonic or baseline pupil diameter change in various conditions. In particular, baseline pupil diameter can be taken as an overall indicator of current arousal levels (Granholm & Steinhauer, 2004). For example, prior research has consistently shown that under conditions of fatigue or low levels of alertness and arousal, baseline pupil diameter is smaller and more variable than when alert (Hou, Freeman, Langley, Szabadi, & Bradshaw, 2005; Morad, Lemberg, Yofe, & Dagan, 2000). Additionally, in sustained attention tasks tonic pupil size tends to decrease and overall pupil variability tends to increase with time on task demonstrating a vigilance decrement (Fried et al., 2014; Unsworth & Robison, 2016). These changes in baseline pupil diameter are consistent with increases in pupillary unrest, suggesting that as time on task increases, alertness, and arousal decrease and

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fluctuations in attention increase (Hopstaken, van deer Linden, Bakker, & Kompier, 2015a; Hopstaken, van deer Linden, Bakker, & Kompier, 2015b; Lowenstein, Feinberg, & Lowenfeld, 1963; McLaren, Erie, & Brubaker, 1992; Morad et al., 2000; Wilhelm et al., 2001; Unsworth & Robison, 2016). Similarly, changes in pre-trial baseline pupil diameter have been linked to lapses of attention and mind-wandering (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013; Grandchamp, Braboszcz, & Delorme, 2014; Kristjansson, Stern, Brown, & Rohrbaugh, 2009; Mittner et al., 2014; Unsworth & Robison, 2016, 2017a, 2018; Unsworth, Robison, & Miller, 2018; van den Brink, Murphy, & Nieuwenhuis, 2016).

While much prior research has examined how baseline pupil diameter changes within participants, additional research has examined between participant differences in baseline pupil diameter and how these are potentially indicative of differences in cognitive abilities and neuromodulatory systems. For example, Stelmack & Mendelzys, 1975 found that introverts had larger baseline pupil diameters than extroverts and suggested that introverts had higher tonic levels of arousal than extroverts. Liakos and Crisp (1971) found a positive correlation between pupil size and neuroticism scores in a control group (although there were no differences between neurotic psychiatric patients and controls in baseline pupil diameter). Simpson and Molloy (1971) found that a high anxiety group had larger pupil size than a low anxiety group. Similarly, Yechiam and Telpaz (2011) found that high-risk takers had larger baseline pupil diameters than low-risk takers. A number of studies have found that persons with Autism Spectrum Disorder have larger baseline pupil diameters than age-matched controls (Anderson & Colombo, 2009; Anderson, Colombo, & Unruh, 2013).

A number of studies have suggested that individual differences in baseline pupil diameter are related to variation in cognitive abilities. For example, in his review of the field, Janisse (1977) noted a study by Crough (1971) in which individuals with low reasoning ability had larger pupillary responses while solving Raven Progressive Matrices problems than individuals with high reasoning ability (see also Ahern & Beatty, 1979). Similarly, Janisse (1977) reported a study by Peavler and Nellis (1976), who found a positive correlation between baseline pupil size and intelligence in a sample of 17 participants. Thus, there seems to be some evidence of relations between pupil diameter and intelligence scores. More recently, Heitz, Schrock, Payne, and Engle (2008) found that high working-memory capacity individuals had larger baseline pupil diameters than low working-memory capacity individuals (see also Tsukahara, Harrison, & Engle, 2016). Likewise, van der Meer et al. (2010) found that individuals with high fluid intelligence had larger baseline pupil diameters than individuals with low fluid intelligence (see also Bornemann et al., 2010; Tsukahara et al., 2016). Thus, a number of between participant studies have suggested that variation in baseline pupil diameter is related to various cognitive abilities and personality traits.

At the same time, it is important to note that these effects do not always replicate. For example, Janisse (1977) noted additional studies that did not find such a relation. Specifically, Boersma, Wilton, Barham, and Muir (1970) examined high- and low-intelligence children (who differed in IQ by 40 points) and found no differences in resting-pupil size. Simpson and Molloy (1971) also found no differences between high- and low-intelligence groups. Additionally, Unsworth and Robison (2017a) had participants perform a number of cognitive ability measures and measured pupillary responses during two attention control tasks (Stroop and the psychomotor vigilance task). While prior research suggested a positive relation between working memory and baseline pupil diameter, Unsworth and Robison (2017a) found that pretrial baseline pupil diameter was negatively correlated with working-memory capacity. Unsworth and Robison (2017a) further reported that pretrial baseline pupil diameter was positively related to neuroticism and mind-wandering but was not related to attention control or fluid intelligence. Thus, while some studies suggest a positive relation between cognitive abilities and baseline pupil diameter, other studies suggest either a negative correlation or no correlation. Of course, like any measure, baseline pupil diameter is not a pure measure given that many factors influence it even under conditions of constant luminance, such as age, overall physical size of the pupil, ingestion of caffeine or nicotine, etc. (Loewenfeld, 1993; Tryon, 1975).

Overall results from prior studies are consistent with the notion that pupil dilations reflect arousal levels and attentional state. Recent research also has suggested that pupil dilations are indirectly related to the functioning of the locus coeruleus norepinephrine (LC-NE) system (Alnaes et al., 2014; Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Jepma & Nieuwenhuis, 2011; Joshi, Li, Kalwani, & Gold, 2016; Murphy, Robertson, Balsters, & O’Connell, 2011; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Reimer et al., 2016; Samuels & Szabadi, 2008; van den Brink et al., 2016; Unsworth & Robison, 2016; Varazzani, San-Galli, Gilardeau, & Bouret, 2015). The LC-NE system seems to be particularly important for sustained attention and alertness (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Chamberlain & Robbins, 2013; Samuels & Szabadi, 2008; Szabadi, 2013). The LC is a brainstem neuromodulatory nucleus that is responsible for most of the NE released in the brain, and it has widespread projections throughout the neocortex, including frontal-parietal areas (Berridge & Waterhouse, 2003; Samuels & Szabadi, 2008; Szabadi, 2013). In terms of pupillary responses, research suggests that when LC tonic levels are low and arousal is low, baseline pupil diameter is small. However, when individuals are hyperaroused and tonic LC levels are very high, overall baseline pupil diameter is relatively large. When LC tonic levels are more optimal and arousal is thought to be at intermediate levels, overall baseline pupil diameter is at intermediate levels. Indeed, recent neuroimaging work has shown that activity in the LC is correlated with changes in pupil diameter (Alnæs et al., 2014; Murphy et al., 2014). Collectively, this work suggests that baseline pupil diameter can be seen as an indirect index of LC-NE functioning.

Baseline pupil diameter during resting state also has been linked to the functioning of the LC-NE system, as well as the default mode network, the frontal-parietal network, and the salience network. For example, Yellin, Berkovich-Ohana, and Malach (2015) had participants fixate on a small dot on the screen for 8 min. Yellin et al. found that pupil diameter fluctuated considerably during the task, and participants reported a high degree of mind-wandering. Importantly, Yellin et al. found that spontaneous fluctuations in pupil diameter correlated positively with BOLD fluctuations in default mode areas. In another resting state study, Schneider et al. (2016) found that pupil dilations (but not overall pupil size) was related to activity in the frontal-parietal network and to activity in the salience network. Breeden, Siegle, Norr, Gordon, and Vaidya (2017) found that fluctuations in spontaneous pupillary dilations were related to activity in cingulo-opercular regions, and this coupling was related to individual differences in inattentiveness as measured by the Adult ADHD Self-Report Scale. Similarly, Kuchinsky, Pandža, and Haarmann (2016) found that increased pupil dilation was related to increased activity in cingulo-opercular regions and decreased activity in the default mode network. Thus, prior research suggests a link between baseline pupil diameter (and changes in pupil diameter) and activity in the LC, as well as activity in the default mode network, frontal-parietal network, and the salience network.

Recently, we have suggested that individual differences in the functioning of the LC-NE system may be a key reason for individual differences in working memory capacity and attention control (Unsworth & Robison, 2017b). Specifically, we have suggested that low working memory capacity and low attention control are related to a dysregulation of LC activity such that low-ability individuals demonstrate more fluctuations in tonic LC activity than high-ability individuals. In support of this claim, we have found that variability in pretrial baseline pupil diameter (rather than overall mean pretrial baseline pupil diameter) were negatively related to working memory capacity and to attention control (Unsworth & Robison, 2015, 2017a). The results from Heitz et al. (2008) and Tsukahara et al. (2016), however, suggest that low working-memory individuals have lower tonic LC levels than high working-memory individuals. Thus, as noted previously, there is a clear discrepancy between these results. One key difference between these studies is that whereas Unsworth and Robison (2015, 2017a) examined pretrial baselines during attention demanding tasks, baseline pupil differences in Heitz et al. (2008) and Tsukahara et al. (2016) also were assessed preexperimentally in which participants simply stared at a fixation point before engaging in any task. Thus, one main goal of the present study was to examine potential relations between baseline pupil diameter and cognitive abilities (in particular working-memory capacity and attention control).

Spontaneous eye blink rate

Dopamine has long been seen as an important neuromodulator of the frontal cortex and linked to overall working memory functioning and attention control (Robbins & Arnsten, 2009). Like NE, dopamine is thought to modulate signal to noise ratios in target neurons (gain modulation) in response to salient events (in particular motivationally salient events), leading to an increase in alertness (Bromberg-Martin, Matsumoto, & Hikosaka, 2010; Servan-Schreiber, Printz, & Cohen, 1990). Whereas NE has typically been associated with overall arousal levels, dopamine has typically been associated with reward processing. More recent research suggests that dopamine is critically important for updating the contents of working memory via an adaptive gating mechanism (Cohen, Aston-Jones, & Gilzenrat, 2004). In this account, dopamine acts to gate input to frontal areas allowing the contents of working memory to be updated in a selective manner. It is assumed that gating occurs via reinforcement learning such that gating occurs when there is an opportunity for reward ensuring that in future reward contexts, gating and updating are more likely to occur (D'Ardenne et al., 2012). Furthermore, dopamine may be particularly important for decision making regarding the costs and benefits of engaging in effortful cognitive activities (Westbrook & Braver, 2016). For example, Varazzani et al. (2015) demonstrated that dopaminergic neurons in the substantia nigra were sensitive to expected reward and the cost of engaging in effortful processes, whereas NE neurons in the LC were sensitive to effort production to energize behavior. As such, dopamine seems critically important for not only ensuring active maintenance of goal states in frontal cortex, but also for updating the contents of working memory via reinforcement learning and decision making of under what circumstances the allocation of effort is worthy, whereas the LC-NE system may be more important for allocating resources and energizing behavioral responses. Thus, dopamine and NE are both likely important for working memory and attention control, but they may be associated with different aspects of control. In terms of individual differences, dopamine is likely important for the active maintenance of task goals seen as a hallmark of individual differences in working memory capacity. Indeed prior research has suggested that individual differences in working memory capacity are related to baseline levels of dopamine (Broadway, Frank, &

Cavanagh, in press; Cools & D'Esposito, 2011; Cools, Roberts, & Robbins, 2008; Kimberg, D'Esposito, & Farah, 1997; Landau, Lal, O'Neil, Baker, & Jagust, 2009). Furthermore, recent research suggests that individual differences in working memory capacity are linked with control mechanisms that are thought to be mediated via phasic dopamine activity (Braver, 2012; Braver, Gray, & Burgess, 2007; Redick, 2014; Richmond, Redick, & Braver, 2015). Thus, dopamine is likely critically important for individual differences in working memory capacity and attention control (Cools, 2016; Cools & D'Esposito, 2011).

Whereas pupil diameter is seen as an indirect measure of LC-NE functioning, spontaneous eye blink rate has been suggested as an indirect measure of the dopamine system (see Jongkees & Colzato, 2016 for a review). In particular, baseline eye blink rate assessed with participants staring at a computer screen for several minutes has been shown to be related to various aspects of personality and to performance on various cognitive tasks. For example, prior research has sometimes found that spontaneous eye blink rate (EBR) is related to extraversion, neuroticism, and psychoticism, yet these relations do not always replicate (Jongkees & Colzato, 2016). In terms of cognitive abilities, Dreisbach et al. (2005) found that EBR was positively related to cognitive flexibility in a task switching paradigm, but EBR was negatively related to cognitive stability. Tharp and Pickering (2011) also demonstrated a positive relation between EBR and task switching and a negative relation between EBR and cognitive stability. Tharp and Pickering found no relation between EBR and performance on the operation span task measure of working memory. Similarly, Zhang et al. (2015) found that EBR was positively related to task switching and performance on the Stroop task and a go/no-go task but was negatively related to performance on a three-back working memory task (although no relation was found with a mental counters task). However, Colzato, van den Wildenberg, van Wouwe, Pannebakker, and Hommel (2009) found that higher EBR was related to reduced inhibitory control in a go/no-go task. Complicating matters further, Dang, Xiao, Liu, Jiang, and Mao (2016) found an inverted U-shaped relation with performance on the antisaccade task but only after participants first performed a difficult version of the Stroop task. Thus, similar to studies examining baseline pupil diameter, there are inconsistent relations between baseline EBR and various cognitive abilities including working memory and attention control (Jongkees & Colzato, 2016).

One potential reason for these discrepant results is that much prior EBR research has relied on relatively small sample sizes. For example, in their recent review of the field, Jongkees and Colzato (2016) demonstrated that the average sample size for studies examining EBR and cognitive variables was roughly 51. Note that approximately 85 participants are needed detect a correlation of 0.30, with power of 0.80 and alpha set at 0.05 (two-tailed). Thus, it seems likely that many prior studies may be underpowered to detect the effect of interest. Similarly, many prior EBR studies have relied on median splits to compare high and low EBR participants. These types of analyses can be problematic for a number of reasons (MacCallum, Zhang, Preacher, & Rucker, 2002). For example, when using a median split, a great deal of individual differences information is lost given that participants within a particular group are treated as equal when they are not. MacCallum et al. (2002) also noted that median splits can have negative impacts on effect size estimates, power, and the inability to examine non-linear relations. Given these types of issues, Jongkees and Colzato (2016) have suggested that future EBR research examine the full distribution of participants and rely on regression techniques rather than simply relying on median splits.

Fixation stability

The final oculometric examined in the current study was fixation stability. Fixation stability refers to the ability to maintain fixation on a stimulus for a brief amount of time. In these studies, participants typically stare at a central fixation point for a short amount of time and various measures of stability (or dispersion; Holmqvist et al., 2011), including standard deviation of eye position are examined. In some conditions, distractor stimuli are flashed on the periphery to try and capture gaze and attention. Whereas baseline pupil diameter and EBR are thought to be associated with different neuromodulatory systems, fixation stability is thought to index the ability to suppress unwanted saccades (and microsaccades) reliant on efficient functioning of the frontal eye fields and the superior colliculus (Krauzlis, Goffart, & Hafed, 2017) and thus should be related to attention control abilities more broadly. For example, Di Russo, Pitzalis, and Spinelli (2003) had elite shooters and control participants stare at a fixation point for 1 min. In the standard condition, participants were simply instructed to maintain their fixation on the central point and the standard deviation of eye position (averaged across both vertical and horizontal dimensions) was the dependent measure of interest. In the distractor condition, stimuli were flashed near the central point and participants were instructed to maintain fixation on the central point. Di Russo et al. found that in both conditions elite shooters were better at maintaining their gaze on the fixation point and having better fixation stability than control participants. Additional research has suggested that Schizophrenic patients (Benson et al., 2012; Barton et al., 2008), individuals with attention deficit hyperactivity disorder (ADHD) (Munoz, Armstrong, Hampton, & Moore, 2003), patients with Autism Spectrum Disorder (Shirama, Kanai, Kato, & Kashino, 2016), individuals with obsessive compulsive disorder (Damilou, Apostolakis, Thrapsanioti, Theleritis, &

Smyrnis, 2016), and individuals with high trait anxiety (Laretzaki et al., 2011) all demonstrated poorer fixation stability (more fixation instability) than control participants. Furthermore, Smyrnis et al. (2004) found that poorer fixation stability was related to lower intelligence scores. Examining periods of mind-wandering versus on-task focus, Grandchamp et al. (2014) found some evidence for poorer fixation stability during mind-wandering than when participants reported being on-task. Consistent with this finding, Fransson, Flodin, Semyr, and Pansell (2014) found that increases in fixation instability were associated with increased activity in the default mode network. Thus, there is some evidence that variation in fixation stability is related to various disorders, lowered cognitive ability (lowered attention control), increased mind-wandering, and increased activity in the default mode network.

Present study

In the present study, we investigated whether individual differences in cognitive abilities (working memory and attention control), personality, and self-report assessments (ADHD, trait mind-wandering, and morningness–eveningness) were related to baseline oculometrics (baseline pupil size, spontaneous eye blink rate, and fixation stability). Specifically, based on prior research suggesting a relationship between working memory capacity and baseline pupil diameter (Heitz et al., 2008; Tsukahara et al., 2016), we sought to replicate this finding. As noted previously, while Heitz et al. (2008) and Tsukahara et al. (2016) found a strong positive relation between pre-experimental baseline pupil diameter and working memory capacity, Unsworth and Robison (2017a) found a slight negative correlation between working memory capacity and pretrial baseline pupil diameter. A key difference between these studies was that Heitz et al. (2008) and Tsukahara et al. (2016) examined baseline pupil diameter before any task was completed in the experiment, whereas Unsworth and Robison (2017a) examined baseline pupil diameter before each trial in two attention control tasks. Thus, our first main goal was to see if we could replicate the finding of an association between baseline pupil diameter and working memory capacity. Note, we are aware that Tsukahara et al. (2016) in their third experiment found that fluid intelligence accounted for unique variance in baseline pupil diameter over and above that accounted for by working memory capacity. Although this is an interesting finding that deserves to be examined further, we focused on the relation with working memory capacity given that this relation has been most consistently observed by that group with both Heitz et al. (2008) and Tsukahara et al. (2016), demonstrating a relation in three separate experiments (6 total experiments), whereas Unsworth and Robison (2017a) did not see the same relation with working memory capacity. Furthermore, Unsworth and Robison (2017a) did not see a relationship with attention control abilities. Thus, we also examined attention control abilities given that both Unsworth and Robison (2017a and 2017b) and Tsukahara et al. (2016) suggest that the LC-NE is critical for such a relation. We also examined whether variation in baseline pupil diameter would be related to individual differences in mind-wandering given that there is some evidence of a positive relation between the two variables (Unsworth & Robison, 2017a), and there is some evidence for an association between resting baseline pupil diameter and activity in the default mode network, which is critically important for mind-wandering (Kuchinsky et al., 2016; Yellin et al., 2015). To examine possible relations between baseline pupil diameter and mind-wandering, we measured mind-wandering with thought probes during the attention control tasks and had participants complete a mind-wandering, self-report scale (Carriere, Seli, & Smilek, 2013). Similarly, given prior evidence for a potential relation between ADHD and pupil diameter (Kuchinsky et al., 2016), participants also completed two self-report ADHD scales. Finally, participants completed the Big Five Inventory questionnaire (John, Naumann, & Soto, 2008) and the Morningness-Eveningness questionnaire (Horne & Östberg, 1976) to explore any relations between these measures and baseline pupil diameter. For example, baseline pupil diameter (and arousal) may vary as a function of whether someone is a morning or evening person, and this could influence any other potential relations.

Our second main goal was to examine possible relations between spontaneous EBR and the cognitive ability and self-report measures. As noted previously, a number of studies have demonstrated relations between various cognitive ability measures and EBR. Given theoretical relations between working memory and dopamine as well as attention control and dopamine, one would expect that EBR should be related to these cognitive abilities. Similarly, given prior research suggesting a relation between some personality traits and EBR (e.g., neuroticism and extraversion), we explored whether EBR would be related to our personality measure and to the other self-report measures. Thus, we attempted to replicate and extend prior research that has used EBR as a potential individual differences measure of dopamine.

Our third main goal was to examine potential relations between fixation stability and the cognitive ability and self-report measures. Given that there has been relatively less research on individual differences in fixation stability and their potential associations with cognitive abilities, these analyses were more exploratory in nature. At the same time, given that many attention control tasks require participants to maintain fixation in preparation for a target stimulus (such as a flashing cue in the antisaccade task; Burton, Pandita, Thakkar, Goff, & Manoach, 2008), we hypothesized that individual differences in attention control should be related to fixation stability.

Our final main goal in the current study was to examine individual differences in what participants were thinking about during the baseline eye measure and whether these individual differences were related to any of the oculometrics. Specifically, prior research suggests that during resting state studies participants report a high degree of mind-wandering and thinking of things unrelated to the current task (Delamillieure et al., 2010; Diaz et al., 2013; Gorgolewski et al., 2014; Hurlburt, Alderson-Day, Fernyhough, & Kühn, 2015; Smallwood & Schooler, 2015; Yellin et al., 2015). For example, following an fMRI resting scan, Gorgolewski et al. (2014) had participants complete a questionnaire asking what they were thinking about during the resting scan. They found that individual differences in the different types of self-generated thoughts were related to different neural activity patterns. Additional studies have used retrospective questionnaires and found that participants report engaging in a variety of mental activities during resting states, including thinking of the past, thinking of the future, thinking of positive experiences, thinking of negative experiences, as well as thinking of the on-going task (Delamillieure et al., 2010; Diaz et al., 2013). Thus, it is critically important to assess what participants are thinking about during these types of resting/baseline tasks to determine if variation in what participants are thinking about are related to variability the different baseline oculometrics. To examine this, immediately following the baseline eye measure, participants completed a questionnaire about what they were thinking about during the baseline eye measure.

Method

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

Participants

A total of 208 participants were recruited from the subject-pool at the University of Oregon, a comprehensive state university. Data from two participants were dropped, because they had more than 90% missing data on the baseline eye measure. Data from two additional participants were dropped, because they only had data for one measure likely due to a mistyped subject number. The remaining 204 participants were 66.5% female, between the ages of 18 and 27 years ($M = 19.09$, $SD = 1.75$), and received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 2 hours. We tested participants over two full academic quarters, using the end of the second quarter as our stopping rule for data collection. We determined that a minimum sample size of 191 participants would be sufficient to find a correlation of 0.20, with power of 0.80 and alpha set at 0.05 (two-tailed). We chose a correlation of 0.20 given that many individual differences correlations are around 0.20-0.30 (Gignac & Szodorai, 2016) and given that Tsukahara et al. (2016) found a correlation of 0.24 between a working memory composite and baseline pupil size. Participants were not specifically screened for history of psychiatric/neurological disorders, medication, or substance use. Participants were allowed to wear glasses or contacts. Data are available on the Open Science Framework.

Materials and procedure

After signing informed consent, all participants completed the baseline eye measure, operation span, symmetry span, reading span, a value-based immediate free recall task, a visual working memory task, the psychomotor vigilance task, antisaccade, and then filled out a battery of questionnaires. All tasks were administered in the order listed above. The value-based immediate free recall task and the visual working memory task were part of another project and are not discussed.

Baseline eye measure

Participants saw a black square on a grey background (mean luminance of the stimuli was 40 cd/m^2) in the center of the screen. Participants were instructed to simply stare at the square. Specifically, participants were told, “In this task we simply want you to look at the square on the screen for a few minutes. Please do not avert your eyes from the screen and do not close your eyes. Although you may blink normally.” The task lasted for 5 min. Pupil diameter and eye gaze were continuously recorded binocularly at 120 Hz using a Tobii T120 eyetracker, integrated in a 17-inch TFT monitor. Participants were seated approximately 60 cm from the monitor in a dim room (illuminance = 30 lux) and did not use a chinrest or other immobilization device. The Tobii T120 provides accurate tracking even with a good degree of head movement. Average pupil diameter and standard deviation of pupil diameter were examined for each 30-s period of the task. Missing data points due to blinks, off-screen fixations, and/or eyetracker malfunction were removed and not included in the pupil averages. Consistent with prior research, blinks were considered as continuous periods of time of at least 100 ms and less than 500 ms in which pupil diameter and eye gaze information was missing for both eyes (Jongkees & Colzato, 2016; Peckham & Johnson, 2016; Smilek, Carriere, & Cheyene, 2010). Blink rate for each 30-s period was computed, and spontaneous EBR was computed as the average eye blink rate for each minute. Finally, 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 for each 30-s period of the task (Di Russo et al., 2003). Missing data points due to blinks, off-screen fixations, and/or eyetracker malfunction were removed and not included in the fixation stability averages.

Baseline eye measure questionnaire

Immediately following the baseline eye measure, participants filled out a brief questionnaire asking what they were thinking about during the eye task. Specifically, participants were first asked "During this task were you mind-wandering/daydreaming?" Participants circled yes or no. Next participants were instructed: Please Circle the statement(s) that best describe what you were thinking of.

- I was totally focused on the task
- I was thinking of something negative related to the past
- I was thinking of something positive related to the past
- I was thinking of something negative related to the future
- I was thinking of something positive related to the future
- I was distracted by sights/sounds/temperature or by physical sensations (hungry/thirsty)
- My mind was blank and I wasn't thinking of anything
- I was drowsy and not very alert.

Finally, participants were instructed to "Please briefly describe what you were thinking about."

Working-memory capacity tasks

Operation span Participants solved a series of math operations while trying to remember a set of unrelated letters (Unsworth, Heitz, Schrock, & Engle, 2005; Redick et al., 2012). 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 (Unsworth, Redick, Heitz, Broadway, & Engle, 2009; Redick et al., 2012). In the symmetry-judgment task, participants were shown an 8 x 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 x 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 (Unsworth et al., 2009; Redick et al., 2012). Half of the sentences made sense (e.g., "Spring is her favorite time of year because flowers begin to bloom."), whereas the other half did not ("Even though she was in trouble, she managed to go to the dice and shop."). 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 that we used in the operation span and symmetry span tasks.

Attention control (AC) tasks

Psychomotor vigilance task (PVT) The psychomotor vigilance task (Dinges & Powell, 1985) is a measure of sustained attention. Participants were presented with a row of zeros on screen, and after a variable amount of time, the zeros began to count up 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. Interstimulus intervals were randomly distributed and ranged from 1 to 10 s. The entire task lasted for 10 minutes for each individual (roughly 75 total trials). The dependent variable was the average reaction time for the slowest 20% of trials (Dinges & Powell, 1985). Roughly 12 thought probes were randomly presented after trials.

Antisaccade In this task (Kane, Bleckley, Conway, & Engle, 2001) participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200-2200

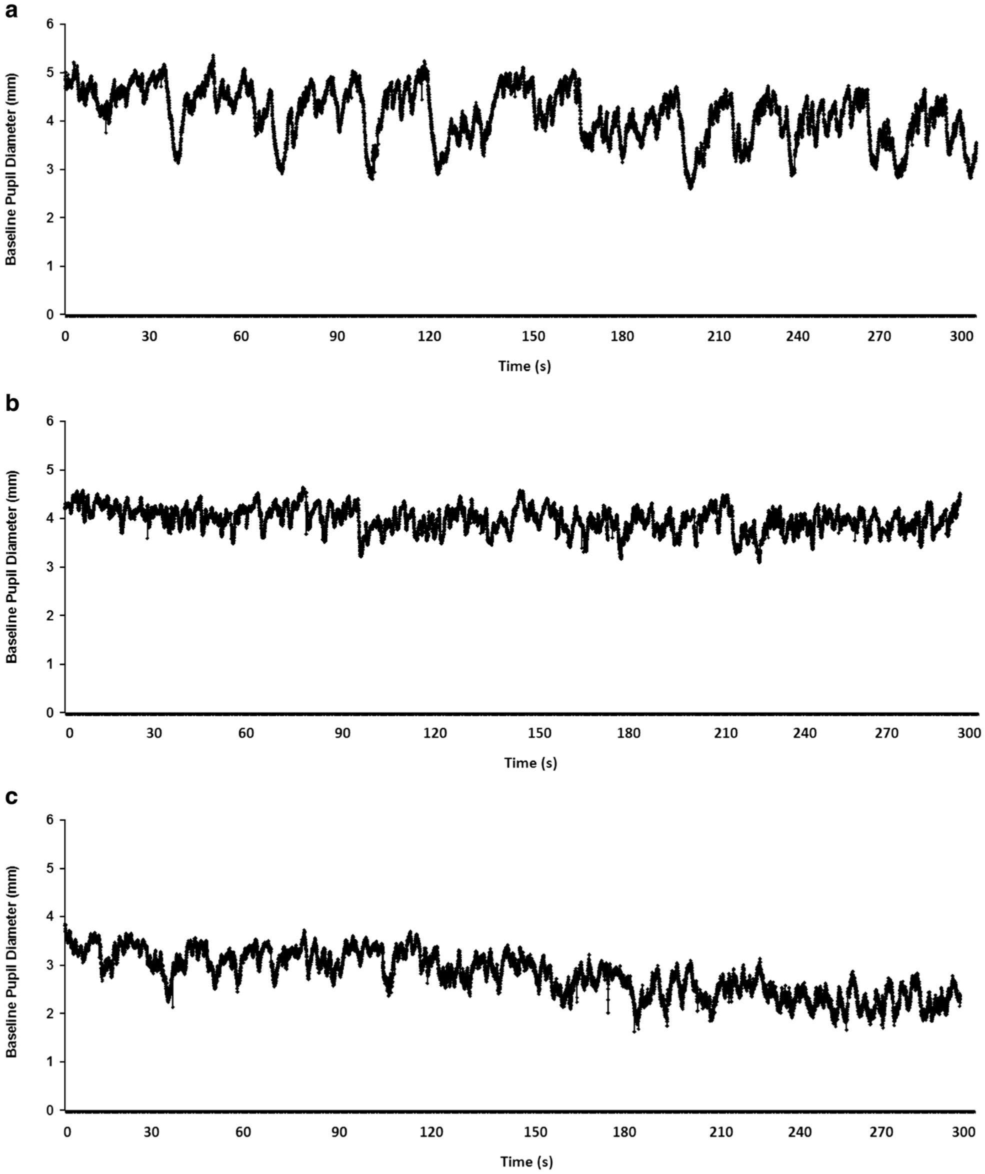

Fig. 1 Baseline pupil diameter for three different participants (**a**–**c**) during the baseline eye measure

ms). A flashing white "=" was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms. 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 and 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.

Thought probes During the attention control 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

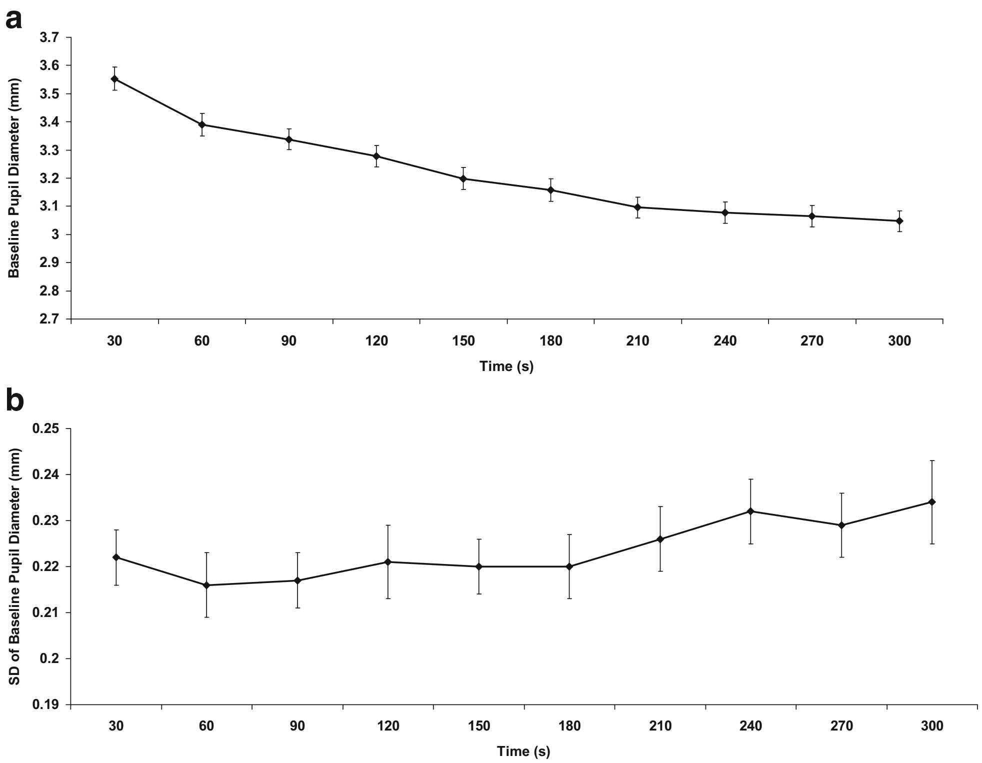

Fig. 2 **a** Baseline pupil diameter as a function of time. **b** Standard deviation of baseline pupil diameter as a function of time. Error bars reflect one standard error of the mean

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. Responses 3-5 were considered as off-task thinking. Prior research has demonstrated that the different off-task probes are correlated and share considerable variance (Unsworth & McMillan, 2014). Thus, responses 3-5 were combined into a single off-task measure for each attention control task.

Self-report questionnaires

Personality Participants completed the 44-item Big Five Inventory (BFI; John et al., 2008). The BFI contains 8 items to measure extraversion, 9 items to measure agreeableness, 9 items to measure conscientiousness, 8 items to measure neuroticism, and 10 items to measure openness. Participants rated how well each item (e.g., "I see myself as someone who is talkative") described them on a 5-point scale (1 = disagree strongly, 5 = agree strongly).

Morningness-eveningness questionnaire This questionnaire consists of 19 items to assess individual differences in morningness and eveningness (Horne & Östberg, 1976). Questions are designed to assess preferences for sleep and waking times, alertness, and peak performance. Lower scores indicate evening types and higher scores indicate morning types.

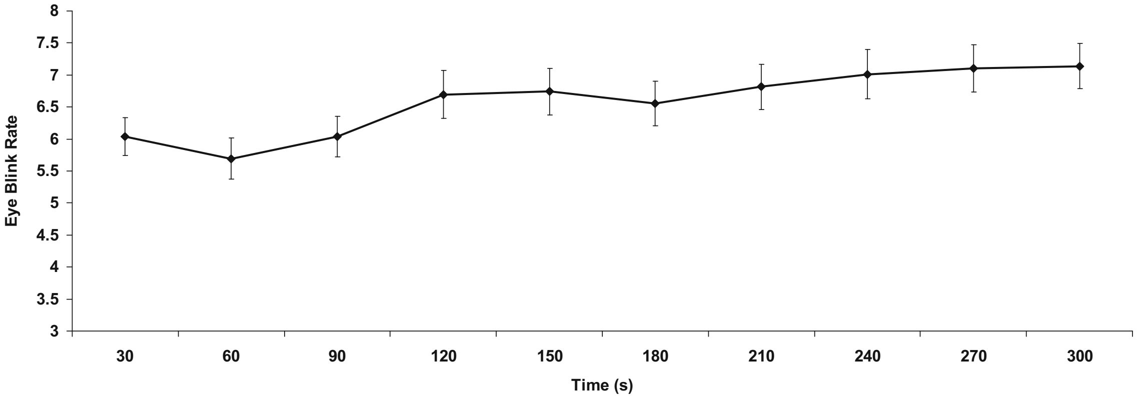

Fig. 3 Eye blink rate as a function of time. Error bars reflect one standard error of the mean

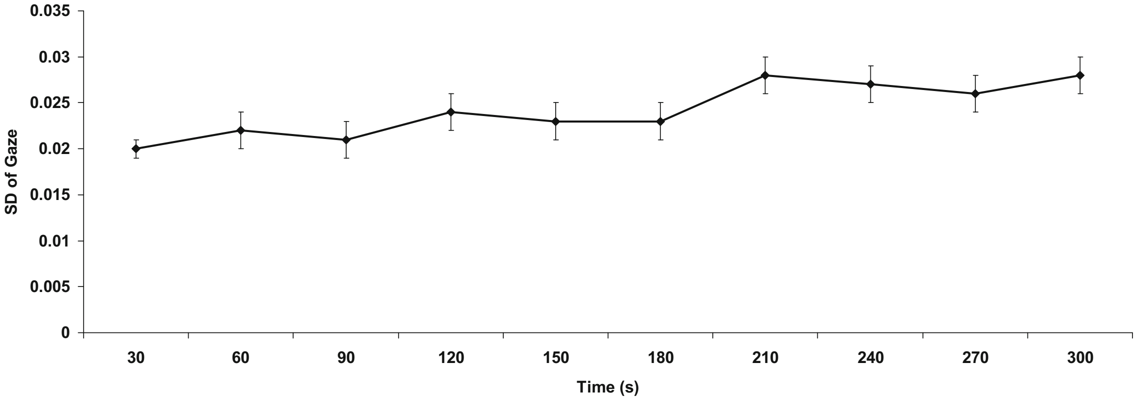

Fig. 4 Standard deviation of gaze as a function of time. Error bars reflect one standard error of the mean

Attention deficit/hyperactivity disorder symptomology Participants completed two ADHD symptomology questionnaires. First, participants completed the adult version of the Attention Deficit/Hyperactivity Rating Scale (AD/HD-RS; DuPaul, Power, Anastopoulos, & Reid, 1998). The AD/HD-RS is an 18-item scale that asks participants to rate the frequency of each behavior (inattentiveness, hyperactivity, impulsiveness) based on a 4-point Likert-type scale. Participants also completed the Adult ADHD Self-Report Scale (ASRS; Kessler et al., 2005), which is an 18-item scale that assesses adult self-reports of ADHD symptomology. In the present sample, the two measures were strongly correlated ($r = 0.76$) and were combined into a single measure. Higher scores indicate greater ADHD symptomology.

Table 1 Descriptive statistics and reliability estimates for all measures

Measure	M	SD	Skew	Kurtosis	Reliability	N
Ospan	37.56	7.47	−0.64	.42	0.61	203
Symspan	19.70	4.76	−0.48	.02	0.50	203
Rspan	36.09	9.00	−0.93	.96	0.74	203
Anti	0.48	0.14	0.33	−0.52	0.73	197
PVT	527.46	165.39	2.86	11.06	0.88	199
Antioff	2.89	3.69	1.09	−0.21	0.75	197
PVToff	3.70	3.40	1.17	1.37	0.63	199
Extraversion	3.35	0.86	0.04	−0.76	0.88	180
Agreeableness	4.00	0.59	−0.52	0.35	0.82	180
Conscientiousness	3.69	0.57	−0.22	−0.01	0.75	180
Neuroticism	2.95	0.80	−0.03	−0.60	0.82	180
Openness	3.47	0.63	0.17	−0.68	0.75	180
MorningEvening	46.11	8.21	0.58	1.48	0.80	186
AD/HD-RS	30.54	7.20	1.02	1.41	0.84	185
ASRS	42.76	9.82	0.68	0.54	0.85	185
MWD	19.23	5.05	−0.68	−0.09	0.84	185
MWS	17.94	5.12	−0.22	−0.19	0.80	185
BaselinePupil	3.21	0.49	0.86	1.15	0.99	200
BaselinePupilSD	0.32	0.12	1.75	5.26	0.93	200
EBR	13.17	8.39	1.19	2.15	0.96	200
GazeSD	0.03	0.03	2.76	8.68	0.95	200

Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; PVT = psychomotor vigilance task; Antioff = off-task thoughts Antisaccade; PVToff = off-task thoughts psychomotor vigilance task; MorningEvening = Morningness-Eveningness Questionnaire; AD/HD-RS = Attention Deficit/Hyperactivity Rating Scale; ASRS = Adult ADHD Self-Report Scale; MWD = mind-wandering deliberate scale; MWS = mind-wandering spontaneous scale; BaselinePupil = average of baseline pupil diameter; BaselinePupilSD = standard deviation of baseline pupil diameter; EBR = spontaneous eye blink rate; Gaze SD = standard deviation of gaze

Deliberate and spontaneous mind wandering To assess self-reports of mind-wandering, participants completed the Mind Wandering: Deliberate (MW-D) and the Mind Wandering: Spontaneous (MW-S) scales (Carriere et al., 2013). The MW-D includes four items that are related to intentional mind wandering, such as: “I allow my thoughts to wander on purpose.” The MW-S includes four items that are related to unintentional mind wandering, such as: “I find my thoughts wandering spontaneously.” A 7-point Likert scale is used for both. Higher scores indicate higher rates of mind wandering.

Results

Time course of each eye measure

First, we investigated potential changes in each eye measure over the course of the 5-min baseline task. For example, shown in Fig. 1 are baseline pupil data for three individual participants. Some participants demonstrated quite a bit of variability in baseline pupil diameter, whereas others show little variability. Additionally, some participants demonstrate a decrease in baseline pupil diameter with time, whereas others show little changes. Changes in both variability of baseline pupil diameter and overall baseline pupil diameter are consistent with differences in overall alertness (Eggert, Sauter, Popp, Zeitlhofer, & Danker-Hopfe, 2012; Wilhelm et al., 2001).

Table 2 Correlations among the cognitive ability measures and self-report questionnaires

Measure	1	2	3	4	5	6	7	8	9	10	11	12
1. WMC	--											
2. AC	**0.29**	--										
3. Off	-0.08	**-0.38**	--									
4. Extraversion	-0.03	-0.01	0.08	--								
5. Agreeableness	-0.07	0.01	-0.05	0.11	--							
6. Conscientiousness	**-0.15**	-0.05	0.01	0.03	**0.25**	--						
7. Neuroticism	0.00	-0.14	**0.15**	-0.09	**-0.20**	-0.02	--					
8. Openness	**0.17**	0.10	-0.14	-0.13	0.08	-0.10	-0.02	--				
9. MorningEvening	-0.04	-0.07	-0.04	0.10	**0.15**	**0.34**	-0.04	0.02	--			
10. ADHD	0.07	0.03	0.10	0.13	-0.11	**-0.48**	**0.30**	0.10	-0.14	--		
11. MWD	0.10	0.09	-0.02	-0.07	**-0.24**	**-0.24**	0.09	**0.22**	**-0.19**	**0.23**	--	
12. MWS	0.02	0.02	0.13	-0.04	-0.05	**-0.24**	**0.15**	0.12	-0.03	**0.43**	**0.37**	--

WMC = working-memory capacity; AC = attention control; Off = off-task thoughts; MorningEvening = Morningness-Eveningness Questionnaire; AD/HD-RS = Attention Deficit/Hyperactivity Rating Scale; ASRS = Adult ADHD Self-Report Scale; MWD = mind-wandering deliberate scale; MWS = mind-wandering spontaneous scale. Correlations significant at the $p < 0.05$ level are bolded

To get a better sense of these changes we first looked at changes in overall baseline pupil diameter over the course of the 5 min. As shown in Fig. 2a, there was a general decrease in baseline pupil diameter over the course of the 5 min, $F(9, 1683) = 140.24$, $MSE = 0.04$, $p < 0.001$, partial $\eta^2 = 0.43$. Examining change in the standard deviation of baseline pupil diameter suggested a nonsignificant effect, $F(9, 1683) = 1.64$, $MSE = 0.004$, $p = 0.10$, partial $\eta^2 = 0.009$. Although the overall main effect of time was not significant, there was a significant linear trend, $F(1, 187) = 6.57$, $MSE = 0.007$, $p = 0.011$, partial $\eta^2 = 0.03$. Additionally, examining the coefficient of variation rather than just standard deviation suggested an effect of time, $F(9, 1683) = 10.19$, $MSE = 0.001$, $p < 0.001$, partial $\eta^2 = 0.05$, in which the linear trend was significant, $F(1, 187) = 58.86$, $MSE = 0.001$, $p < 0.001$, partial $\eta^2 = 0.24$. Thus, there was some evidence that variability in baseline pupil diameter increased over the course of the 5 min. Overall, the decrease in pupil diameter and the general increase in pupil variability are consistent with increases in pupillary unrest as time on task increases, suggesting that as time on task increases, alertness and arousal decrease (Eggert et al., 2012; Lowenstein et al., 1963; McLaren et al., 1992; Morad et al., 2000; Yoss, Moyer, & Hollenhorst 1970.; Wilhelm et al., 2001).

Next, we examined changes in EBR over the course of the 5 mins. As shown in Fig. 3, EBR tended to increase over the

Table 3 Correlations among the eye measures

Measure	1	2	3	4
1. BaselinePupil	--			
2. BaselinePupilSD	**0.24**	--		
3. EBR	**0.23**	-0.07	--	
4. GazeSD	-0.10	**0.24**	**0.30**	--

BaselinePupil = average of baseline pupil diameter; BaselinePupiSD = standard deviation of baseline pupil diameter; EBR = spontaneous eye blink rate; Gaze SD = standard deviation of gaze. Correlations significant at the $p < 0.05$ level are bolded

Table 4 Correlations of the eye measures with the cognitive ability and self-report questionnaires

	Eye measure			
	BaselinePupil	BaselinePupilSD	EBR	GazeSD
WMC	0.01	0.02	-0.10	-0.04
AC	-0.10	-0.01	**-0.17**	**-0.18**
Off	**0.17**	-0.01	0.12	0.01
Extraversion	0.02	0.01	**0.16**	0.04
Agreeableness	0.01	0.07	0.07	-0.12
Conscientiousness	-0.06	0.02	0.02	-0.02
Neuroticism	0.13	-0.05	0.12	-0.02
Openness	-0.08	-0.01	0.04	0.03
MorningEvening	-0.11	0.02	-0.14	-0.05
ADHD	**0.15**	0.03	0.07	0.05
MWD	-0.07	-0.03	-0.02	0.09
MWS	0.06	-0.03	-0.03	-0.06

WMC = working-memory capacity; AC = attention control; Off = off-task thoughts; MorningEvening = Morningness-Eveningness Questionnaire; AD/HD-RS = Attention Deficit/Hyperactivity Rating Scale; ASRS = Adult ADHD Self-Report Scale; MWD = mind-wandering deliberate scale; MWS = mind-wandering spontaneous scale; BaselinePupil = average of baseline pupil diameter; BaselinePupilSD = standard deviation of baseline pupil diameter; EBR = spontaneous eye blink rate; Gaze SD = standard deviation of gaze. Correlations significant at the $p < 0.05$ level are bolded course of the 5 min, $F(9, 1791) = 6.72$, $MSE = 7.39$, $p < 0.001$, partial $\eta^2 = 0.03$. Similarly, examining fixation stability in terms of the standard deviation of gaze position over time suggested an overall increase in the standard deviation, $F(9, 1683) = 6.23$, $MSE = 0.000$, $p < 0.001$, partial $\eta^2 = 0.03$ (Fig. 4).

Correlations with cognitive abilities and self-report questionnaires

Next, we turn to our primary results of interest in terms of individual differences relations between the baseline eye measures and the cognitive ability measures and the self-report questionnaires. Shown in Table 1 are the descriptive statistics for all measures. 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 (i.e., skewness < 2 and kurtosis < 4). Mean and standard deviation of baseline pupil diameter were similar to several prior reports (Bornemann et al., 2010; van der Meer et al., 2010; Yechiam & Telpaz; Unsworth & Robison, 2015, 2017a), especially under similar luminance conditions (Reilly, Kelly, Kim, Jett, & Zuckerman, in press; Winn, Whitaker, Elliott, & Phillips, 1994). Although both were smaller than what was seen in Heitz et al. (2008) and Tsukahara et al. (2016; see *Discussion*). Mean and standard deviation of eye blink rate also was consistent with prior research (Jongkees & Colzato, 2016).

Consistent with prior research we created a working-memory capacity (WMC) composite given that the three working memory span measures were correlated (Operation span – Symmetry span $r = 0.40$; Operation span – Reading span $r = 0.45$; Symmetry span – Reading span $r = 0.34$). 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 0.74, 0.60, and 0.66, respectively. Likewise, we computed a factor composite for attention control (Antisaccade – Psychomotor Vigilance task $r = -0.35$, factor loadings 0.56 and −0.56) and for off-task thoughts (Antisaccade – Psychomotor Vigilance task $r = 0.38$, factor loadings 0.66 and 0.66). We also created a factor composite for the two ADHD measures (AD/HD-RS - ASRS $r = 0.76$, factor loadings 0.87 and 0.87).

Shown in Table 2 are the correlations among the cognitive ability measures and the questionnaires. Note these correlations are Spearman rhos rather than the typical Pearson correlations, because Spearman rhos tend to be more robust to nonnormal distributions, presence of outliers, and potential nonlinear relations (de Winter, Gosling, & Potter, 2016). Working memory capacity and attention control were related consistent with prior research (Unsworth & Spillers, 2010). Off-task thoughts during the attention control tasks were related to attention control abilities but not to working memory capacity, which is somewhat inconsistent with prior research (Unsworth & McMillan, 2014; Randall, Oswald, & Beier, 2014). The cognitive ability measures demonstrated only a few relations with the self-report questionnaires, and interestingly, off-task thoughts during the attention control tasks were not related to self-reports of mind-wandering. Self-reports of mind-wandering were, however, related to self-reports of ADHD symptomology consistent with prior research (Seli, Smallwood, Cheyne, & Smilek, 2015).

Examining correlations among the eye measures (Table 3) suggested that most of the measures were positively related except that baseline pupil diameter and fixation stability were not related and EBR and the standard deviation of baseline pupil diameter were not related.

Next, examining correlations between the eye measures and the cognitive ability and self-report questionnaires suggested generally weak and mainly nonsignificant relations.[1] Specifically, only 5 of the possible 48 correlations were significant (Table 4). These included a positive correlation between baseline pupil diameter and off-task thoughts consistent with prior research (Unsworth & Robison, 2017a) and a positive correlation between baseline pupil diameter and ADHD symptomology. Variability in baseline pupil diameter did not significantly correlate with any of the measures. EBR correlated negatively with attention control abilities and positively with extraversion somewhat consistent with prior research (Jongkees & Colzato, 2016). Finally, fixation instability was negatively correlated with attention control abilities suggesting that participants with higher attention control abilities tended to have greater fixation stability. We also examined whether the proportion of off-screen fixations was related to any of the variables. That is, although 99% of the fixations were onscreen, sometimes individuals looked away from the monitor. The proportion of off-screen fixations was only correlated with attention control abilities ($r = -0.28$, $p < 0.001$; all other *p*s > 0.15). Thus, individuals with better attention control abilities tended to have greater fixation stability and were less likely to look off-screen than individuals with poor attention control.

Theoretically, the relations between NE and dopamine with performance are thought to be nonlinear (at least within participants). Thus, we also examined whether baseline pupil diameter and EBR exhibited quadratic relations with any of the measures. For baseline pupil diameter, the vast majority of quadratic effects were nonsignificant (*p*s > 0.17). The only measures to demonstrate quadratic effects were Extraversion

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[1] We also examined the results separately for males and females. Overall, the same general pattern of weak relations were found for both males and females; the only main difference was that fewer correlations were significant for males. This is to be expected given that our sample was composed of 66.5% females, and thus there was a much lower N for males.

(β = −0.20, p = 0.02) and Conscientiousness (β = 0.24, p = 0.01). For EBR, the only measure to come close to demonstrating a quadratic effect was Openness (β = −0.16, p = 0.09); none of the other p values were close to significance (ps > 0.45).

Note, given the large number of correlations that were examined, it is likely that some of these relations are a result of a Type I error. Using a strict Bonferroni correction suggested only one correlation (attention control abilities to the proportion of off-screen fixations) would remain significant. Additionally, using a stricter alpha level, such as $p < 0.005$, suggested only that one correlation would be deemed significant. In general, there were weak and nonsignificant relations between the cognitive ability and self-report questionnaires with the eye measures, and those correlations that were significant may not be very robust.

Correlations with post-task questionnaire

The final set of analyses examined the post-task questionnaire in terms of what participants were thinking about during the 5-min baseline measure. Table 5 shows the descriptive statistics for the different questions; 19% of participants indicated being focused on the eye task, whereas 79% of participants indicated that they mind-wandered at some point during the task. Positive thoughts tended to occur more frequently than negative thoughts, $t(192) = 7.20$, $p < 0.001$, and future thoughts tended to occur more frequently than past thoughts, $t(192) = 4.37$, $p < 0.001$. Participants also indicated being distracted (27%), experiencing mind-blanking (17%) and being drowsy (18%). Thus, it is clear that participants experience a number of different thoughts and states during baseline resting task such as this (Delamillieure et al., 2010; Diaz et al., 2013).

Next, we examined whether variation in responses to the post-task questionnaire would be related to any of the baseline eye measures. Table 6 shows the resulting correlations. Most of the relations were weak and nonsignificant. Similar to the prior analyses, only 5 of the possible 36 correlations were significant. These included a negative correlation between baseline pupil diameter and task focus, a positive relation between baseline pupil diameter and mind-wandering during the task, a positive relation between baseline pupil diameter and distraction during the task, and a negative correlation between baseline pupil diameter and mind-blanking during the task. These results are generally consistent with the prior results, suggesting that baseline pupil diameter is positively related to off-task thoughts with individuals who are most likely to experience off-task thoughts (mind-wandering and distraction) having the largest baseline pupil diameters during the baseline eye measure. The only other significant correlation was a positive correlation between fixation instability and drowsiness, suggesting that individuals who indicated they were drowsy during the task were more likely to have more variable fixation patterns. Similar to the above analyses, when using a strict Bonferroni correction, none of the correlations would remain significant. Additionally, using an alpha level, such as $p < 0.005$, also suggested that none of the correlations would be considered significant. Thus, there were weak and mostly nonsignificant relations between the post-task questionnaire responses and the eye measures.

Table 5 Descriptive statistics post-task questionnaire

Measure	M	SD	Skew	Kurtosis
Focused	0.19	0.39	1.62	0.64
Mind wandering	0.79	0.41	−1.42	0.01
Past negative	0.11	0.32	2.45	4.04
Past positive	0.23	0.42	1.31	−0.30
Future negative	0.13	0.34	2.16	2.68
Future positive	0.46	0.50	0.18	−1.99
Distraction	0.27	0.46	1.05	−0.92
Mind blank	0.17	0.37	1.81	1.29
Drowsy	0.18	0.38	1.71	0.95

For completeness, we also examined relations between the post-task questionnaire responses and the cognitive ability and self-report measures. These analyses suggested that those participants who indicated they were focused on the eye task were likely to be morning types (r = 0.17). Those participants who indicated they were mind-wandering during the eye task were more likely to experience off-task thoughts during the attention control tasks (r = 0.15), were lower in conscientiousness (r = −0.15), and tended to be more open (r = 0.18). Those participants who indicated they were thinking of past negative thoughts tended to have higher self-reported ADHD symptoms (r = 0.29) and more likely to spontaneously mind-

Table 6 Correlations of the eye measures with responses on the post-task questionnaire

	Eye measure			
	BaselinePupil	BaselinePupilSD	EBR	GazeSD
Focused	**-0.16**	-0.02	-0.05	0.05
Mind wandering	**0.15**	-0.05	0.02	-0.10
Past negative	0.04	-0.04	-0.02	0.02
Past positive	0.07	0.07	-0.12	-0.08
Future negative	0.01	-0.06	0.02	-0.02
Future positive	0.12	0.05	0.12	-0.05
Distraction	**0.16**	0.04	-0.11	-0.04
Mind blank	**-0.17**	-0.06	-0.02	0.04
Drowsy	-0.04	-0.03	0.05	**0.16**

BaselinePupil = average of baseline pupil diameter; BaselinePupilSD = standard deviation of baseline pupil diameter; EBR = spontaneous eye blink rate; Gaze SD = standard deviation of gaze. Correlations significant at the $p < 0.05$ level are bolded wander (r = 0.21). Responses to the past positive question were not related to any of the measures (all r's < 0.13). Similarly, responses to the future negative question were not related to any of the measures (all r's < 0.13). Participants who indicated they were thinking of future positive thoughts tended to be more open (r = 0.20). Participants who indicated they were distracted during the baseline eye task tended to be more neurotic (r = 0.21). Participants who indicated that their minds were blank during the baseline eye measure tended to report less deliberate (r = −0.16) and less spontaneous mind-wandering (r = −0.15). Finally, participants who indicated they were drowsy during the baseline eye measure tended to have lower attention control abilities (r = −0.20), tended to experience more off-task thoughts during the attention control tasks (r = 0.26), and tended to have higher self-reported ADHD symptoms (r = 0.17). Thus, what participants were thinking about during the baseline eye task tended to be related to some of the cognitive ability and self-report questionnaire measures.

Discussion

In the current study, we examined whether normal variation in baseline oculometrics, such as baseline pupil diameter, eye blink rate, and fixation stability, would be related to individual differences in cognitive abilities (working memory capacity and attention control), off-task thinking, and various self-report assessments. Overall, the results were fairly straightforward in suggesting that the oculometric indicators demonstrated weak and largely nonsignificant relations with the cognitive ability and self-report measures. Specifically, examining baseline pupil diameter suggested that the only significant correlations were positive relations with off-task thinking during the attention control tasks, ADHD symptomology, and self-reports of mind wandering and distraction during the baseline task. Negative relations with baseline pupil diameter were demonstrated with self-reports of on-task focus and mind blanking during the baseline measure. Thus, those individuals who tend to experience off-task thinking (mind wandering and distraction) tended to have larger baseline pupil diameters than participants who tend to be more focused on the task at hand. These results replicate prior research suggesting a positive relation between baseline pupil diameter and off-task thinking (Unsworth & Robison, 2017a).

Importantly, there was no evidence for a relation between cognitive abilities, such as working memory capacity and attention control with baseline pupil diameter. In the current study, the correlation between baseline pupil diameter and working memory capacity was essentially zero (r = 0.01), and the correlation with attention control also was weak and negative (r = −0.10).[2] In fact, computing Bayes factors for these relations suggested that the evidence was more consistent with the null. For example, the BF01 for the relation between working memory and baseline pupil diameter was 10.32, suggesting that these data are 10.32 times more likely to be observed under the null hypothesis. Likewise, the BF01 for the relation between attention control and baseline pupil diameter was 2.49. Thus, these results are inconsistent with prior research, which has suggested a positive relation between baseline pupil diameter and working-memory capacity (Heitz et al., 2008; Tsukahara et al., 2016). Indeed, in the current study, those individuals with larger baseline pupil diameters tended to experience more off-task thoughts and less task focus than individuals with smaller baseline pupil diameters, which is directly opposite of what prior research would suggest. One difference between the current study and prior research is that in the current study we measured baseline pupil diameter over 5 min, whereas Heitz et al. (2008) measured baseline pupil diameter over 7 s, and Tsukahara et al. (2016; Experiment 3) measured baseline pupil diameter over 30 s. Given changes in baseline pupil diameter with time-on-task, it is possible that this longer measurement session could have influenced the results. Thus, we examined the relations for only the first 30 s of the baseline task to see if differences would emerge. However, like the overall baseline measure, there were no relations between baseline pupil diameter over the first 30 s with working memory capacity (r = 0.03, p = 0.70; BF01 = 9.3) or with attention control (r = 0.01, p = 0.90; BF01 = 10.46). These results clearly suggest that within the current dataset, there is not a relation between baseline pupil diameter and working-memory capacity. As such, these results suggest that the prior relations seen in two previous studies (Heitz et al., 2008; Tsukahara et al., 2016) may not be as robust as initially thought.

At present, it is not clear what may be causing the discrepant results across studies. It is possible that differences in participant samples may be partially driving the results. That is, the present study included all university students from the University of Oregon, whereas the prior studies relied on college students from Georgia Institute of Technology, college students from other universities in Atlanta, and from Atlanta community volunteers. Thus, it is certainly possible that these differences in samples could be leading to different results. To determine whether this was the case, we reanalyzed data from three experiments from Unsworth, Schrock, and Engle (2004) that were conducted in the exact same laboratory at Georgia Institute of Technology and used the exact same eye tracker as

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[2] Because we did not use a chin rest in this study, we also examined whether average distance from the eye tracker influenced the relations with baseline pupil diameter. Average distance from the eye tracker was correlated with baseline pupil diameter (r = −0.19, p = 0.007). However, average distance from the eye tracker was not related to working-memory capacity (r = −0.03, p = 0.69) and was not quite related to attention control (r = 0.13, p = 0.08).

Heitz et al. (2008). In Unsworth et al. (2004), high and low working-memory capacity individuals completed various prosaccade and antisaccade tasks while their eyes were being tracked. Furthermore, these experiments were conducted at the same time as the Heitz et al. experiments and used largely the exact same participants. Given that nearly all eye trackers record pupil diameter, we were able to examine whether there were differences between the high and low working-memory capacity individuals in baseline pupil diameter in each experiment. In Experiment 1 of Unsworth et al. (2004), there were no differences between high ($M = 5.96$, $SD = 1.21$) and low working-memory individuals ($M = 5.91$, $SD = 0.87$), $t(47) = .16$, $p = 0.88$. In Experiment 2, there were differences between high ($M = 6.87$, $SD = 1.27$) and low working-memory individuals ($M = 5.63$, $SD = 1.30$), $t(30) = 2.72$, $p = 0.01$. In Experiment 3, there were no differences between high ($M = 6.14$, $SD = 1.07$) and low working-memory individuals ($M = 6.01$, $SD = 1.17$), $t(62) = 0.44$, $p = 0.66$. Thus, examining data from the same laboratory and same participants as prior research suggested that differences only arose in one of three experiments. Again, this suggests that the positive relation between working memory and baseline pupil diameter is likely not as robust as initially suggested.

One potential issue noted by a reviewer was that the lack of correlation in the current data could be due to restriction of range in baseline pupil diameter. Specifically, the reviewer suggested that because the current mean and standard deviation are lower than what was seen in Tsukahara et al. (2016), it is possible that there is a restriction of range in our baseline pupil diameter measure that limits the ability to find a correlation. In terms of why our mean baseline pupil diameter is lower, the answer is relatively simple. Participants in the current study stared at a black square on a grey background in a dimly lit room. Participants in Tsukahara et al. (2016) stared at a grey fixation on a black background. Thus, differences in mean baseline pupil diameter likely result from differences in luminance. Indeed, the current mean (and standard deviation) are very similar to other reports using similar lighting conditions (Reilly et al., in press). Furthermore, in a recent study we collected pupil measures during the antisaccade task with white stimuli on a black background and the mean pretrial baseline pupil diameter was larger as would be expected ($M = 4.95$, $SD = 0.67$). Mean pre-trial baseline did not correlate with WMC ($r = 0.001$). So, differences in mean baseline pupil diameter between studies likely results from differences in luminance, as well as possible differences in the eye trackers used and other variables, such as distance from the tracker.

In terms of differences in variability across the study samples, one possible reason is age. It is well known that age correlates with baseline pupil diameter (Birren, Casperson, & Botwinick, 1950; Winn et al., 1994). In Tsukahara et al. (2016), the mean age of participants was 24.46 years ($SD = 4.66$). In the current study, the mean age of participants was 19.09 years ($SD = 1.75$). In Tsukahara et al. (2016) age correlated with both baseline pupil diameter ($r = -0.32$) and WMC ($r = -0.32$). In the current study, age did not correlate with either baseline pupil diameter ($r = -0.06$) or WMC ($r = -0.06$). Reanalyzing data from Tsukahara et al. (2016; obtained courtesy of Jason Tsukahara) suggests that WMC is correlated with baseline pupil diameter ($r = 0.22$, N = 327). Importantly, partialling age out of the correlation suggests a drop in the correlation between WMC and baseline pupil diameter ($pr = 0.13$, $p = 0.02$). That is, of the 4.8% of variance shared between WMC and baseline pupil diameter in Tsukahara et al. (2016), 3.2% is shared with age, and only 1.6% is unique to WMC. Thus, most (67%) of the shared variance between WMC and baseline pupil diameter is due to shared variance with age. Heitz et al. (2008) reported a similar analysis in their data where WMC and baseline pupil diameter correlate at $pr = 0.15$ after partialling out age. It should be noted that the Heitz et al. results are likely further inflated given that these correlations are really point-biserial correlations because only high and low WMC participants are included (i.e., mid WMC participants were not tested), which can lead to inflated correlations. Note, we are not suggesting that age completely accounts for the relation between WMC and baseline pupil diameter seen in prior studies given that there is still a significant relation after controlling for age. Rather, we simply note that once age is partialled out, the correlation between WMC and baseline pupil diameter is weaker than previously demonstrated. Again this suggests that the relation between WMC and baseline pupil diameter might not be as robust as previously thought.

These results suggest that a likely reason for the increased variability in baseline pupil diameter, and part of the reason for a correlation between WMC and baseline pupil diameter, reported in Tsukahara et al. (2016) is due to the relation typically seen between baseline pupil diameter and age. Note, both the current study and Tsukahara et al. (2016) have similar limits on age (18-35 years), but the differences in correlations likely come down to how participants were sampled. As noted above, the present study included all university students from the University of Oregon, whereas Tsukahara et al. (2016) relied on college students from Georgia Institute of Technology, college students from other universities in Atlanta, and from Atlanta community volunteers. Unfortunately, the way participants were sampled in Tsukahara et al. (2016) can lead to a confounding of age with ability given that high-ability participants will tend to be younger college students, and low-ability participants will tend to be older community volunteers. Thus, it is partially correct that there is range restriction in the current data, but this range restriction is in terms of age, which is exactly what you would want in order to test for possible individual differences in baseline pupil diameter without the influence of age. Future research is needed to better examine possible relations between baseline pupil diameter and cognitive abilities, such as working memory capacity, and the extent to which various sample characteristics and other factors (e.g., age; task design; participant payments vs. class credit; participant interest and motivation; anxiety, etc.) could be influencing the results. Furthermore, additional future research is needed to better establish the possible role of baseline pupil diameter as an indicator of individual differences in LC-NE functioning.

While we have provided some possible reasons for why differences could arise in both mean and variance of baseline pupil diameter across studies, we note that differences in the correlations across studies could certainly be due to differences in the variance of baseline pupil diameter. That is, because we obtained an overall smaller variance in baseline pupil diameter than prior studies, this could have reduced our ability to find significant relations with baseline pupil dimeter. As such, future research will need to examine what factors (such as luminance and sample characteristics) can lead to changes in variance of baseline pupil diameter and how this impacts the correlation with cognitive abilities such as WMC.

The results for variability in baseline pupil diameter were very straightforward in suggesting that standard deviation of baseline pupil diameter did not correlate with nearly all of the other measures in the current study. The only significant correlations that were found were with mean baseline pupil diameter and standard deviation of gaze. Thus, normal variation in baseline pupil diameter while simply staring at a fixation cross was not related to any of the cognitive ability and self-report assessments, nor was it related to any of the items from the post-task questionnaire.

Examining EBR suggested that only two of the possible relations were significant. Specifically, EBR was negatively correlated with attention control and positively correlated with extraversion. These results are somewhat consistent with prior research (Jongkees & Colzato, 2016). For example, as noted previously, Colzato et al. (2009) found a negative relationship between EBR and attention control (measured with a go/no-go task). At the same time, other studies have found positive relations between attention control and EBR (Zhang et al., 2015). Similarly, prior research found a relationship between EBR and extraversion (Jongkees & Colzato, 2016). While these correlations are interesting and somewhat consistent with prior research, it is important to note that the vast majority of correlations with EBR were weak and nonsignificant. Thus, the current results add to the inconsistent and conflicting pattern of results, suggesting that EBR is related to individual differences in cognitive abilities and various self-report assessments. Future work is needed to better examine the robustness of EBR as a potential indicator of individual differences in dopamine activity (Sescousse et al., 2018) and to explore potential moderating variables.

Similar to the other oculometrics, examining fixation stability suggested only two significant correlations. Specifically, standard deviation of gaze (a measure of fixation instability) was negatively correlated with attention control abilities suggesting that those with higher attention control abilities had better fixation stability. Furthermore, the proportion of off-screen fixations was negatively correlated with attention control, suggesting that not only were high attention control ability participants better able to maintain fixation on the center of the screen, they also were less likely to look off-screen during the duration of the task. These results make sense given the tasks used to measure attention control in the current study. In both the antisaccade and psychomotor vigilance tasks, it is critically important to maintain fixation on the center of the screen while waiting for the target stimulus to appear. If participants are looking at other parts of the screen or off the screen when the target stimulus appears the resulting response will likely be either a very long reaction time or an error. Thus, fixation stability seems essential for performance on these types of attention control tasks. Future research is needed to better examine this possibility. The only other significant correlation with the standard deviation of gaze was a positive correlation with self-reports of being drowsy during the baseline task. Thus, those individuals who were drowsy found it more difficult to maintain their gaze than individuals who felt more rested. Again, it should be emphasized that the vast majority of relations were weak and not significant. Future research is needed to examine the extent to which individual differences in fixation stability during baseline tasks are robust and associated with various other individual differences measures.

The current results also demonstrated the importance of examining what participants are thinking about during the baseline measure. Similar to resting fMRI studies, our post-task questionnaire revealed that during the baseline measure participants reported thinking of a wide variety of things. Overall, 79% of participants indicated that they were mind-wandering during the baseline measure, and this was correlated with baseline pupil diameter. Examining the open-ended responses suggest that participants thought of various things during the baseline measure. These included thinking of relatively mundane things, such as what to eat for lunch (future planning), personal issues (recent fight with a significant other), or more serious issues, such as a friend who had recently been assaulted. Clearly, we cannot simply assume that having participants stare at fixation point for a few minutes is going to provide a pure measure of baseline activity in various neuromodulatory systems. Rather, participants are using this time to think of various things, and these thoughts are likely going to influence the resulting oculometrics. For example, a participant who is planning an upcoming trip will likely be more aroused than someone who is bored, leading to differences in baseline pupil diameter, and these differences may have nothing to do with tonic LC-NE activity. Thus, it is critical for future research to better examine exactly what participants are thinking about during these baseline measures and seeing how this is related not only to the eye measure that is being investigated but also to other relevant individual differences.

Before concluding, we would be remiss if we did not note limitations with the current study. An important issue is that perhaps the lack of significant correlations is because we simply did not measure the appropriate constructs of interest. For example, although prior research has found a correlation between baseline pupil diameter and working memory (Heitz et al., 2008; Tsukahara et al., 2016), a stronger relationship was found between fluid intelligence and baseline pupil diameter (Tsukahara et al., 2016). Thus, perhaps if we had measured fluid intelligence, we might have found the positive relation with baseline pupil diameter. However, we note that in a prior study, we did not observe a relation between baseline pupil diameter measured during two attention control tasks and fluid intelligence (Unsworth & Robison, 2017a). Nevertheless, the fact that we did not measure fluid intelligence in the current study is a limitation, and future research is needed to determine whether there is a robust positive correlation between baseline pupil diameter and fluid intelligence. Likewise, the majority of EBR research that has found a relationship between EBR and performance has focused on cognitive flexibility measures and reward drive behaviors (Jongkees & Colzato, 2016). Thus, had we examined these measures, perhaps we would have found larger and more robust relations with EBR. Future research is needed to examine these relationships more thoroughly. Furthermore, future research should rely on large sample sizes, examine multiple indicators per construct, and examine the full range of subjects (i.e., not rely exclusively on median splits).

Another potential issue with the current study is how we measured EBR. Like other studies in the literature, we relied on eye tracking, and blinks were defined as signal loss lasting between 100-500 ms. Although this type of method has been used before, it is not as accurate as other methods, such as EOG. As noted by Jongkees and Colzato (2016), eye tracking estimates of EBR can be inaccurate given that signal loss can occur for reasons other than blinking (such as poor calibration/tracking, off-screen fixations, etc.). Thus, the lack of robust relations between our EBR measure and the other measures could have arisen due to the use of the method that we used to estimate EBR. Future research is needed to examine the relationship between EBR and various cognitive and dispositional variables with a large sample of participants.

Conclusions

The current study examined individual differences in baseline oculometrics and their relation to cognitive abilities, personality traits, and self-report assessments. Although there were several interesting results, the majority of relations were weak and nonsignificant. Combined with prior research, the current results suggest that relations between different baseline eye measures and various individual differences constructs may not be as robust as initially suggested. In order to fruitfully examine the validity of different baseline oculometrics, we must show that these measures demonstrate robust relations with the constructs of interest. Future research must better examine what participants are thinking about during the baseline eye measure and assess how variability in these different thoughts influence the eye measure of interest and subsequently impact relations with other constructs.

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