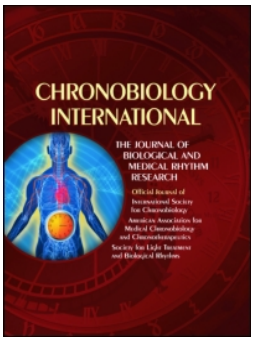

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SHORT COMMUNICATION

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Time-of-day variation in sustained attentional control

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ABSTRACT

Sustained attention is a fundamental cognitive function underlying many activities in daily life including workplace safety, but its natural variation throughout the day is incompletely characterized. To examine time-of-day variation, we collected a large online data set ($N = 6{,}363$) with participation throughout the day and around the world on the gradual-onset continuous performance task, a sensitive measure of sustained attention. This allowed us to examine accuracy, attentional stability, and strategy. Results show that both accuracy and attentional stability peak between 9:00 and 11:00 a.m. and progressively decline throughout the day, whereas strategy is more stable.

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Attentional control; circadian; homeostatic sleep pressure; sustained attentional control; time of day; vigilance

Introduction

As a fundamental cognitive function, sustained attention underlies many essential activities of daily life, from effectively accomplishing work/school activities (Steinmayr et al., 2010) to driver safety (Yanko & Spalek, 2013) to effective social communication (Bennett Murphy et al., 2007). Sustained attention, itself just one aspect of attention, is a complex cognitive function, incorporating physiological arousal, vigilance, and in some cases inhibitory control (Sarter et al., 2001). Particularly when safety is of concern, it is important to know whether the ability to sustain attention tends to vary throughout the day so that risks can be managed. For example, because the risk of accidents varies throughout the day (highest overnight, see Folkard et al., 2006; Lenné et al., 1997), and accident risk is related to lapses in sustained attention (Kahneman et al., 1973; Smilek et al., 2010), monitoring systems have been proposed to detect these lapses in attention to warn those with high-risk jobs before accidents occur (e.g., driving, Sahayadhas et al., 2012; train operators, Wilde & Stinson, 1983).

Though numerous studies have examined the effects of sleep deprivation on attention (e.g., Lim & Dinges, 2008; Pilcher et al., 2007), fewer studies have examined natural fluctuations throughout the day. Those that have examined daily variation have found different results for different aspects of attention. Arousal and alertness, which can be operationalized by measures such as the alerting effect in the Attention Network Task (Matchock & Mordkoff, 2007), and tonic alertness sub-measures of continuous performance tasks (baseline responses to common stimuli, as described in Valdez et al., 2005) have been shown to covary with core body temperature, suggesting true circadian influence (Schmidt et al., 2007; Valdez et al., 2005; Valdez et al., 2008). However, sustained attention tasks, which place more demands on attentional control, such as go/no-go tasks (Sagaspe et al., 2012) and attentional control sub-measures of continuous performance tasks (responding to rare or A-X targets, see Valdez et al., 2005), have shown a different pattern. As with alertness/arousal, performance is worse during the night, but peak performance has shown to occur shortly after waking and worsens over the course of the day, suggesting a main effect of homeostatic sleep pressure, that is, increasing need for sleep due to time awake (e.g., Valdez et al., 2005). Most notably, an elegant forced desynchrony experiment by

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Harrison and colleagues (2007) showed that sustained attention measured with a modified go/no-go task, the Sustained Attention to Response Task (SART, specifically commission errors), worsened with time spent awake. The effect was modified but not driven by circadian phase; for any given number of hours of wakefulness, performance was worst when subjects were 180 degrees from core temperature acrophase (i.e., in the middle of the night, Harrison et al., 2007). This is relevant because many commonly used tests of sustained attention (e.g., SART), including the current study, require attentional control in addition to tonic alertness. Collectively, this previous work suggests that performance on more complex sustained attention tasks decreases with time awake.

There have been several well-controlled studies examining time-of-day variation in attention as discussed above, but these studies have been small with limited demographics. Although a broader sample is desirable from a statistical standpoint, demographics such as age and gender may have pronounced effects on time-of-day and circadian effects in cognition (Schmidt et al., 2009). For example, circadian acrophase may be shifted earlier and amplitude reduced with increasing age (Schmidt, Peigneux, & Cajochen, 2012; Van Cauter, Leproult, & Kupfer, 1996), and chronotype may differ by gender (Adan & Natale, 2002). Furthermore, both age (Fortenbaugh et al., 2015) and gender (Riley et al., 2016) have previously been shown to have significant effects on our laboratory's sustained attention task. We present here a novel way to examine time-of-day variation in cognitive processes, specifically sustained attention, across a large and diverse sample from around the globe using an online data set. In order to make use of this self-selected and demographically diverse sample, we corrected for both age and gender to mitigate any self-selection bias in these important variables (based on our previous work, see Methods), since self-selection bias is a serious concern in such samples (Schofield, 2016).

Previous studies of time-of-day variation in attention have focused on a limited number of measures, most often errors, and reaction time. This is problematic because changes throughout the day in errors and reaction time could reflect strategic changes rather than ability changes (Craig et al., 1981). Further, time-of-day changes may be better reflected in more sensitive attention measures such as reaction time variability. Using the gradual onset continuous performance task (gradCPT, Esterman et al., 2013), we measured a wider array of sustained attention variables than previous studies, including a signal detection approach to accuracy (*d'* and criterion), and multiple reaction time-based measures (mean and variability). Together these measures allow us to separate task ability and strategy, factors that can vary independently. The gradCPT, though similar to other continuous performance tasks such as the SART, differs in that it removes the phasic onsets/offsets between stimulus transitions that can exogenously capture attention. We reasoned that removing these phasic onsets/offsets could better isolate sustained attention. Further, given the rapid pace and gradual nature of the gradCPT, optimal performance is associated with stable reaction times, not necessarily fast or slow reaction times (see Methods for more details). We have previously validated this task in over 20,000 healthy participants aged 10–85 (Fortenbaugh et al., 2015; Riley et al., 2016) and in populations suffering from trauma/depression (DeGutis et al., 2015), showing effects on separable aspects of sustained attention.

Although it is prudent to be wary of selection effects, as mentioned above, the ability to examine time-of-day effects in more naturalistic settings, the potential greater generalizability of the findings, and the increased power available to detect time-of-day effects are important advantages that could provide complementary evidence to the smaller, more tightly controlled within-subject studies (e.g., Button et al., 2013). After accounting for selection effects to the best of our ability, our data allow us to examine variation in multiple aspects of sustained attentional control throughout the day in a large, demographically diverse, albeit self-selected sample.

Methods

Participants

Our participants were 6,363 unpaid volunteers between the ages of 18 and 45 years. Adults under 45 were chosen because performance on our task, the gradual onset continuous performance task (gradCPT), begins to decline sharply around age 45 (Fortenbaugh et al., 2015). We also restricted our sample to under 45 to avoid introducing noise into the data set due to age-related changes in circadian rhythm that may affect middle-aged and older adults beginning after age 40 (Zhou et al., 2003). For a review of effects of age on circadian rhythm, see Campos Costa et al., 2013. Participants visited TestMyBrain.org, a cognitive testing website, over 14 months in 2014 and 2015. TestMyBrain.org is a citizen science website which people can visit voluntarily to become participants in a variety of neurocognitive tasks. The majority (68%) of TestMyBrain.org traffic comes from search engines with the top search terms being "brain tests," "test your brain," and "mind tests". The remaining traffic comes from a variety of social media and news sites, with less than 1.5% of traffic per site. Data from TestMyBrain.org have been shown to be to equivalent to a variety of lab-based perceptual and cognitive tests in terms of mean performance, performance variability, and internal reliability (Germine et al., 2012). Additionally, accuracy measures on the web-based version of the gradCPT match those observed in lab-based settings (Fortenbaugh et al., 2015). While mean RTs were found to be slower on the web-based version, mean reaction time variability was equivalent (numerically lower), suggesting that slower response transmission times do not systematically influence performance (or impact variability). This is in line with other studies, suggesting that reaction times can be reliably measured online (Crump et al., 2013).

Before starting the task, participants gave informed consent according to the guidelines set by the Committee on the Use of Human Subjects at Harvard University and the Wellesley College Institutional Review Board. The consent form and instructions were in English. For each participant we collected age, gender, IP address, whether English was their native language, and ethnicity, but no other biographical information. After completing the gradCPT, each participant was provided with individualized feedback (percentile scores) on how they performed compared to others. Our data set did not include repeat participants or any participants who had a prolonged period (30 seconds or more) without a response. Participants were also excluded if their cognitive task performance deviated more than three standard deviations from the mean either on reaction time, variability of reaction time, omission errors, or commission errors. A total of 87 participants (1.4%) were removed. Of the remaining participants, there were 3,620 men and 2,743 women. IP address (which was not stored) was used to pinpoint latitude and longitude where testing occurred, which was then used to determine the participant's time zone. Using the time zone and the time stamp from the TestMyBrain.org server, we calculated the time of day at which the participant completed the task.

Task and procedure

The gradCPT, designed to measure sustained attentional control, was presented at TestMyBrain.org as previously reported by our group (Fortenbaugh et al., 2015). In the task, participants are shown a series of gray-scale images that gradually transition from one to the next every 800 ms using linear pixel-by-pixel interpolation. Each image is either a city scene (non-target stimulus, 90% of images) or a mountain scene (target stimulus, 10% of images). The gradCPT requires participants to respond by pressing the space bar to city images and withhold their response to mountain images (i.e., a go/no-go task). Because of the stimuli transition quickly, discriminating cities from mountains and withholding one's response to a mountain image is challenging. The gradCPT, in contrast to other continuous performance tasks (e.g., SART), avoids abrupt stimulus onsets that can exogenously capture attention. The task still requires frequent responses, leading to reliable measures of response time. In addition to the gradual and overlapping nature of the task, the rapid pace encourages a consistent reaction time, as reaction times that are too fast (leading to errors of commission to rare mountains) and too slow (leading to errors of omission) are associated with worse accuracy.

Before beginning the main task, each participant was given three 30-second practice sessions. The main task lasted 4 minutes without a break. While this abbreviated version of the task prevents measurement of vigilance decrements, the shorter duration was used in order to balance task completion, participation, and test length using unpaid volunteers on TestMyBrain.org.

Statistical analyses

We calculated six dependent variables for each participant using custom scripts and basic Matlab functions (Mathworks Inc., Natick, MA). First, we calculated two measures of accuracy: commission error rate (the proportion of trials where participants erroneously responded to a mountain scene), and omission error rate (the proportion of trials where participants failed to respond to a city scene). Second, we calculated the mean reaction time (in milliseconds, as detailed previously in Esterman et al., 2013), and the coefficient of variation (CV, i.e., the standard deviation of reaction times divided by the mean reaction time). Reaction times for responses to target images were not included. Finally, we used signal detection analyses to calculate *d'* (which quantifies an individual's ability to discriminate between targets/nontargets independent of response strategy; higher values means better discrimination) and criterion (a measure of response bias or the willingness to respond when uncertain; higher values indicate greater willingness to respond, Macmillan & Creelman, 1991).

For all analyses, we regressed out the effects of age and gender, using age-corrected residuals calculated separately for men and women. These were calculated using our previously published equations (see Supplementary Table S1 in Fortenbaugh et al., 2015, Supplementary Table S1). In particular, to statically remove the effects of age, performance on each gradCPT variable was modeled across the lifespan by separate segmented linear functions and residuals were calculated for each individual. To remove the effects of gender, men's and women's residuals were separately z-transformed (based on mean and SD of each gender) before the two data sets were recombined. Statistically removing the effects of age and gender allowed us to more accurately measure time of day performance variation, since the age and gender composition of the subjects varied throughout the day (Figure S1). Uncorrected data can be seen in Figure S2. A z-score of 0 indicates average performance.

In order to estimate the range of daily variation in absolute units, we calculated the average value of each variable across 24 hours (weighted by number of participants at each time point), using the original non-residualized, non-z-scored data. We then added the residualized maximum and minimum, respectively, calculated from age- and gender-corrected data, to estimate the daily maximum and minimum.

Cosinor analysis

We used cosinor analysis to test for the presence of significant 24-hour variation in each of our six performance variables using the CATKit R package (Lee Gierke & Cornelissen, 2016). We fit 12 data points (2-hour bins across 24 hours, to ensure at least 80 participants per bin) using the equation Y(t) = M + A*cos(2*pi*t/24 + phi), where M is the mesor (midline value), A is the amplitude of the cosinor fit, and phi is the acrophase (Cornelissen, 2014). We assumed a period of 24 hours. We also performed a multiple-component cosinor analysis with 24h, 12h, and 8h periods. In all cases, we calculated the goodness-of-fit (R^2) of the cosinor fit, and the p value, with alpha = 0.05 used to determine significance.

Results

Using latitude/longitude, time zone, and timestamp data from 6,363 participants, we were able to calculate the time of day at which each participant completed the online gradCPT. Participants were between the ages of 18-45 from 40 different countries, with 43.1% women. Participation was lowest between 7:00 and 9:00 a.m. (N = 88) and highest between 5:00 and 7:00 p.m. (N = 817). Because there was variation in the gender and age composition within different time bins and because our previous studies found significant effects of age and gender on performance (Fortenbaugh et al., 2015; Riley et al., 2016), we corrected for both age and gender by regressing out the effects of age separately for men and women (see Methods).

We assessed six variables calculated from each person's gradCPT performance: *d'* and criterion, mean RT, coefficient of variation of reaction time (CV), and commission and omission errors. We have previously found on this task that *d'* and CV are strongly negatively associated and together are considered to reflect sustained attention ability. Mean RT and criterion are weakly correlated with these ability measures and likely reflect task strategy, with a slower mean RT and lower criterion associated with more cautious responding (Fortenbaugh et al., 2015). These strategy and ability variables also dissociate in factor analysis (Fortenbaugh et al., 2015), indicating that it is possible to be accurate and consistent while taking either a cautious or bold task strategy (i.e., slow or fast reaction times). Commission errors are thought to represent brief attentional lapses, while omission may indicate greater levels of task disengagement (Cheyne et al., 2009).

We double-plotted performance in each of these variables throughout the day to better visualize periodicity in the data (Figure 1). Cosinor analysis was used to test for the presence of significant 24 hour variation in each of the six variables. The results showed a cosinor fit with significant nonzero amplitude for commission errors, reaction time, CV and *d'* (Table 1). With multiple component cosinor models, compared with single component models, fewer of the 6 variables had a fit with significant non-zero amplitude, and there was no significant periodicity of either 12 or 8 hours for any variable (all $p > 0.05$, data not shown). Additionally, we compared the multiple component and single component models using the F test to determine whether the increase in R^2 in the more complex models was significant (Cohen, Cohen, West, & Aiken, 2003). In no cases did the complex models explain significantly more variance after adjusting for degrees of freedom (all $p > 0.2$, data not shown). Collectively these analyses strongly support the presence of a single 24-hour rhythm.

In the variables reflecting sustained attention ability, CV and *d'*, performance peaked between 9:00 and 11:00 a.m. (lowest CV and highest d'). Throughout the day, until 11:00 p.m., performance decreased slowly, with CV rising and *d'* falling. After 11:00 p.m., performance decreased more rapidly, deteriorating until 5:00-7:00 a.m.. Between 7:00 and 9:00 a.m., performance improved abruptly. From the lowest value to the highest value, performance varied by approximately 0.3 standard deviations in each variable, corresponding to a difference of 0.014 in CV (Cohen's $d = 0.27$), and a difference of 0.28 in *d'* (Cohen's $d = 0.21$). These effect sizes are slightly smaller than the well-controlled within-subjects study reported by Harrison and colleagues (2007), likely due to increased variance in our more heterogeneous sample.

The strategy-related variables RT and criterion had a different pattern, with slowest RTs around mid-day and fastest RTs near midnight. RT varied by only 14.5 ms from peak to trough, reflecting a more subtle effect (Cohen's $d = 0.11$). Unlike the ability-related variables with abrupt transitions in performance (between 5:00-9:00 a.m.), the changes in RT were more gradual which was reflected in a higher R^2 and cosinor fit for this variable (Table 1). Although there was no significant daily variation in criterion, the trend was similar to that of RT, with more cautious responding near noon and more liberal responding later in the evening. Response strategy was highly variable during the night.

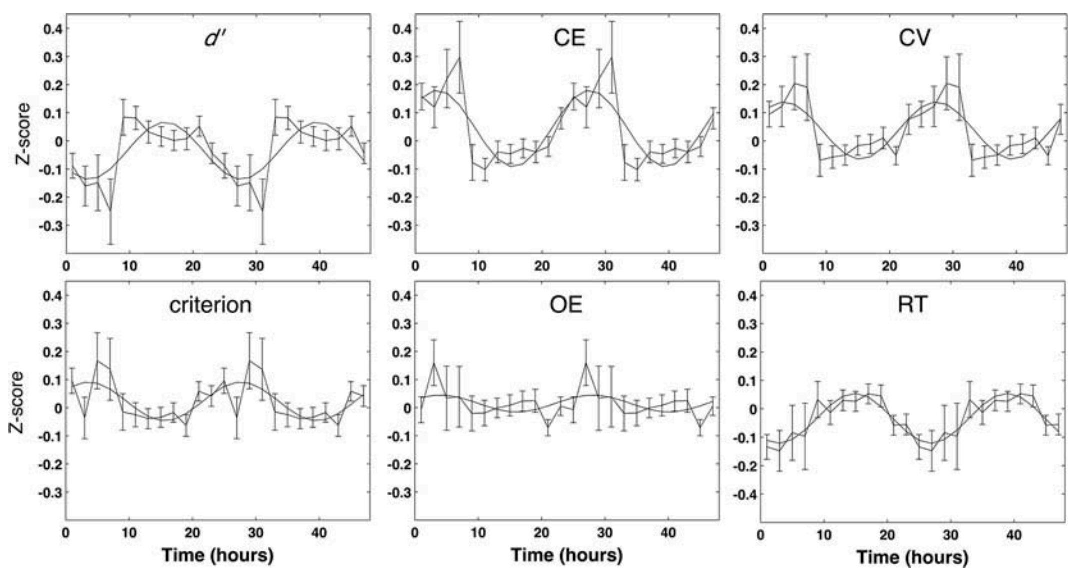

Figure 1. Time-of-day variation in six gradCPT variables. Data are shown double-plotted in two-hour intervals with cosinor fit overlaid. CE—commission errors, CV—coefficient of variation of reaction time, OE—omission errors, RT—reaction time. Mean ± SEM. $N = 6,363$, $N > 88$ in each bin.

Table 1. Cosinor fit amplitude, *p*-value and R^2 for six gradCPT variables.

Variable	Range (native units)	Amplitude (z score)	Zero-amplitude test *p* value	R^2
d'	3.02-3.25	0.10	0.031	0.50
criterion	0.14-0.15	0.07	0.060	0.44
CE	21%-26% errors	0.14	0.009	0.61
OE	1.7%-2.6% errors	0.03	0.45	0.17
RT	866-880 ms	0.09	<0.001	0.81
CV	0.14-0.15	0.10	0.017	0.59

Bold p-values < 0.05. CE—commission errors, CV—coefficient of variation of reaction time, OE—omission errors, RT—reaction time.

The variation in commission errors was very similar to that of the ability-related variables, with the fewest errors occurring between 9:00-11:00 a.m. and increasing errors throughout the rest of the day and night. Throughout the day the commission error rate rose from ~21% to 26% (Cohen's d = 0.28). There was no significant pattern of daily variation in omission errors.

Range of daily variation in each variable is shown in Table 1 (see Methods). All of these results were replicated, albeit with greater noise, within age-limited subgroups (when comparing 18-27-year olds, 28-36-year olds and 37-45-year olds, see Figure S3). The pattern was also replicated when the analysis was repeated with 1-hour and 3-hour time bins (Figure S4).

Discussion

In this study, we found significant daily variation in sustained attentional control, specifically commission errors, reaction time, coefficient of variation, and *d'*. The best group-level performance on all sustained attention ability metrics occurred mid-morning (9:00-11:00 a.m.), and worsened slowly until late evening, when performance declined more precipitously. Performance across all variables was the worst in the early morning hours (3:00-7:00 a.m.).

These results are consistent with those of Harrison and colleagues (2007), using a well-controlled within-subjects design using a small sample (N = 18). Harrison et al. used a modified Sustained Attention to Response Task (SART) and experimentally altered sleep-wake cycles to show that performance was modulated by circadian rhythm. In particular, they found that for any given number of hours awake, performance was worst when 180 degrees out of phase. Importantly, however, when subjects were on a typical schedule (not an experimental schedule), performance worsened with time awake. Consistent with this study, we found that commission errors were lowest mid-morning and increased throughout the day. We extend these results by also showing that reaction time variability (CV) and *d'* also peak around 9:00-11:00 a.m. and worsen throughout the day. Since the commission error rate reported in Harrison et al. (2007) may be influenced by strategic changes (Wilson et al., 2016), our *d'* and CV findings are particularly notable in that they clearly demonstrates a time-of-day effect in attentional ability. When examining task strategy, as indexed by criterion and mean reaction time (RT), we found only subtle changes throughout the day, with trends suggesting a more cautious approach around noon and more liberal response strategy around midnight. Thus, our results also suggest that it is mainly task ability, and not strategy, that worsens throughout the day in this particular pattern.

Is the variation in sustained attention ability throughout the day circadian, or the result of homeostatic sleep pressure? The work by Harrison et al. (2007) suggests that the effect is homeostatic. Other groups have also shown that increasing homeostatic sleep pressure causes sustained attentional control to worsen, especially in the context of sleep deprivation (Chuah et al., 2006; Sagaspe et al., 2012). There is also a great deal of evidence in the literature showing that performance on the Psychomotor Vigilance Test (PVT) worsens as homeostatic sleep pressure increases (e.g., Burke et al., 2015; Doran et al., 2001) and may not be under circadian control (Valdez et al., 2005). A homeostatic effect explains our data well, since performance begins to worsen in the morning and becomes much worse around midnight, at which point our participants are likely experiencing strong sleep pressure.

Commission errors have been interpreted in two distinct ways in the literature, as either attentional lapses or as lapses in inhibitory control. Several groups have studied daily variation in inhibitory control using more traditional inhibition tasks (e.g., stop-signal, Stroop task) and found that it is either under circadian and not homeostatic control (Burke et al., 2015; Hasher et al., 1999) or not affected by either circadian or homeostatic factors (Bratzke et al., 2012). In the current study, we found that the time of day results in commission errors had a very similar pattern to measures of sustained attention ability (CV and *d*'). Both effects, peaking in the morning and worsening throughout the day, are more consistent with an influence of homeostatic sleep pressure than circadian rhythm. Therefore, we suggest that the current study supports the interpretation of a time-of-day effect in commission errors as a marker of poor sustained attention rather than lapses in inhibitory control.

The current results could shed light on the daily variation in accident literature. Studies across professions (e.g. Hänecke et al., 1998) have similarly found that the fewest accidents occur in the morning and increase through the day. An important future goal would be to examine the degree to which daily variation in sustained attention ability predicts these accidents and to implement diagnostics or interventions to monitor sustained attention and reduce accidents.

Our results showed that sustained attention strategy had more subtle daily variation than the ability variables, with the slowest reaction times and most cautious responding between noon and 4:00 p.m. This is in contrast to Harrison and colleagues (2007) and Manly and colleagues (2002) which did not show any significant effect of time awake or circadian phase on mean reaction time. In contrast to Harrison et al.'s findings using the SART, several reports using the PVT demonstrate true circadian variation in reaction time, showing that that reaction time is *fastest* in the late afternoon (Silva et al., 2010; Squarcini et al., 2013). Importantly, in the SART, fast reaction times have been related to increased errors whereas in the PVT, faster RTs are a measure of better performance. This makes direct comparisons of reaction time across these studies challenging. An additional study of circadian effects on a continuous performance task found that there was circadian modulation of reaction time, with the fastest reaction times around 7:00-9:00 p.m. (Valdez et al., 2012). One notable detail about the current paradigm that could explain why the RT results differ from these studies is that RT on the gradCPT is linked to strategy rather than ability (Fortenbaugh et al., 2015). In particular, slower reaction times reflect more careful performance, and faster reaction times do not necessarily reflect better performance. In fact, using similar not-X paradigms, some find faster RTs are related to greater lapses in sustained attention (Cheyne et al., 2009).

Although the results of the current study are promising, they have limitations. The primary limitation is that we are not able to fully exclude the possibility of selection effects. It is reassuring that our results remained significant after we statistically removed the effects of age and gender. Despite this, and consistent with prior reports, it is possible that factors other than true daily variation in cognition contributed to the effect we observe (e.g., chronotype). If selection effects were present, our results might still offer a naturalistic view of variation in sustained attention throughout the day due to all causes, which may be a predictor of relevant outcomes such as workplace accidents. Future studies of this type should include more demographic variables particularly demographic categories related to circadian rhythm, such as the Morningness–Eveningness Questionnaire (Shahid, Wilkinson, Marcu, & Shapiro, 2011) for optimal analysis. In addition to this limitation, we are not able to definitively distinguish circadian and homeostatic effects using our methods. We are only able to identify patterns consistent with circadian and/or homeostatic effects discussed in the literature.

In summary, we found evidence within our large online data set that sustained attentional control is strongest mid-morning and worsens thereafter, likely due to homeostatic sleep pressure, with important implications for safety.

Declaration Of Interest

The authors declare no conflict of interest.

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