Accepted version of the following publication:

Smit, A.N., Michalik, M., Livingstone, A.C., Mistlberger, R.E. & McDonald, J.J. (2020). Circadian misalignment impairs ability to suppress visual distractions. *Psychophysiology*, *57(2)*, e13485. https://doi.org/10.1111/psyp.13485

Circadian misalignment impairs ability to suppress visual distractions

Andrea N. Smit[1], Mateusz Michalik[1], Ashley C. Livingstone[1], Ralph E. Mistlberger[1], John J. McDonald[1]*

[1]Department of Psychology, Simon Fraser University, Burnaby, BC, V5A1S6, Canada

*Correspondence and requests for materials should be addressed to John McDonald, Simon Fraser University, 8888 University Drive, Burnaby, BC, Canada, V5A 1S6, tel: 778-782-9802, e-mail: jmcd@sfu.ca.

Abstract

Evening-type individuals often perform poorly in the morning because of a mismatch between internal circadian time and external social time, a condition recognized as social jetlag. Performance impairments near the morning circadian (~24h) trough have been attributed to deficits in attention, but the nature of the impairment is unknown. Using electrophysiological indices of attentional selection (N2pc) and suppression (P_D) we show that evening-type individuals have a specific disability in suppressing irrelevant visual distractions. More specifically, evening-type individuals managed to suppress a salient distractor in an afternoon testing session, as evidenced by a P_D, but were less able to suppress the distractor in a morning testing session, as evidenced by an attenuated P_D and a concomitant distractor-elicited N2pc. Morning chronotypes, who were well past their circadian trough at the time of testing, did not show this deficit at either test time. These results indicate that failure to filter out irrelevant stimuli at an early stage of perceptual processing contributes to impaired cognitive functioning at non-optimal times of day, and may underlie real-world performance impairments, such as distracted driving, that have been associated with circadian mismatch.

Impact Statement

Evening-type individuals perform poorly in the morning, when their internal circadian time is out of synch with external time. Their performance decrements have been attributed to an attention deficit, but the specific nature of the deficit is unknown. Here we show that evening-type individuals retain the ability to search for salient visual search targets but not the ability to suppress a salient distractor in the morning. The suppression deficit was observed three hours after the beginning of morning rush-hour in the region, indicating that evening types commute at a time when their ability to prevent distraction is compromised.

The circadian clock that regulates daily sleep-wake cycles in humans also affects performance on a variety of tasks. Performance is generally best in the early evening, and worst in the early-morning hours before normal waking (Burke, Scheer, Ronda, Czeisler, & Wright, 2015; Chellappa, Morris, & Scheer, 2018; Czeisler & Dijk, 2001), with the precise timing of the peak and trough varying substantially across individuals (i.e. chronotype; Schmidt, Collette, Cajochen, & Peigneux, 2007). The degree to which people exhibit a morning chronotype or evening chronotype (or anything in between) is defined, to a large degree, by the period length of that individual's circadian clock (Duffy, Rimmer, & Czeisler, 2001; Hida et al., 2013). Morning-type individuals tend to wake up early and show optimal performance throughout the daytime, whereas evening-type individuals tend to wake up later, especially on free days, and show optimal performance in the afternoon and evening. On regular school and work days, however, many evening-type individuals must wake up closer to their circadian trough and perform at non-optimal times of day (Duffy, Dijk, Hall, & Czeisler, 1999; Kerkhof & Van Dongen, 1996). Performance impairments near the circadian trough have been attributed to deficits in attention, but the nature of the attentional impairment is unknown.

The present study sought to determine the nature of attentional deficits that occur when individuals perform at a non-optimal time of day, relative to the timing of their circadian peak and trough. The research was premised on the prevailing view that inhibitory control processes are generally more susceptible to impairment than facilitatory processes (Engl, 2002; Eysenck, Derakshan, Santos, & Calvo, 2007; Gaspar, Christie, Prime, Jolicoeur, & McDonald, 2016; Hasher, Zacks, & May, 1997; Logan, Schachar, & Tannock, 1997). In line with this *compromised-control hypothesis*, prior research has demonstrated how aging (Gazzaley et al., 2005; Hasher et al., 1997), anxiety (Eysenck, Cooney, Rissman, & D'Esposito, 2007; Gaspar & McDonald, 2018), and attention deficit disorder (Wang et al., 2016) can impair inhibitory control processes (i.e. suppression of distractions) while leaving other abilities intact. Here, we hypothesized that although individuals may retain the ability to search the visual environment for target objects of interest at non-optimal times of day (Horowitz, Cade, Wolfe, & Czeisler, 2003), the inclusion of a salient visual distractor may reveal an inhibitory visual-search impairment that has so far gone unnoticed.

As a natural model of circadian misalignment, we recruited participants who reported sleep-wake patterns most indicative of morning or evening chronotype as measured by the Munich Chronotype Questionnaire (MCTQ; Roenneberg, Wirz-Justice, & Merrow, 2003). Both groups were tested in the morning (9 AM) and in the late afternoon (4 PM), with the order of the testing sessions counterbalanced across participants within each group. These test times were chosen for ecological validity, as they correspond to the beginning and ending of a normal work or school day for most people. Because evening chronotypes wake-up closer to their daily minimum of attentional performance on work days, the morning testing session was misaligned with this group's optimal testing time.

Event-related potentials (ERPs) were recorded during a visual search task to assess processing of target and distractor items. The analyses focused on display configurations in which either the target or the distractor appeared to the left or right of fixation, and, the other stimulus appeared above or below fixation. Such configurations make it possible to isolate lateralized changes in the ERP waveforms associated with processing of the lateral stimulus, even when no overt response to that stimulus is required (Hickey, Di Lollo, & McDonald, 2009; Woodman & Luck, 2003). Attending to a lateral stimulus is known to trigger a contralateral negativity called the N2pc (Luck, 2012; Luck & Hillyard, 1994), while actively ignoring a lateral stimulus is known to trigger a contralateral positivity called the P_D in same general time range (Gaspar et al., 2016; Gaspar & McDonald, 2014; Hickey et al., 2009). We predicted that if evening-type individuals are unable to properly suppress irrelevant distractors in the morning, as would be expected from the compromised-control perspective, then a distractor-elicited P_D should be reduced and a distractor-elicited N2pc should emerge. We further predicted that morning types would exhibit little or no evidence of impairment because the daytime test sessions occurred later in their circadian cycle.

Methods

The Research Ethics Board at Simon Fraser University approved the research protocol used in this study. All experimental procedures were performed in accordance with guidelines and regulations outlined by SFU and the Natural Sciences and Engineering Research Council of Canada.

Participants

Four hundred fifty-four undergraduate students filled out the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2003) and midsleep times on free days (MSF) were used to identify the most extreme morning and evening chronotypes. Individuals with history of head trauma, diagnosed mental illness, sleep disorder, or who were currently using sleep aid medication were excluded from invitation into the study. Sixty-four individuals from the extreme ends of the sample's MSF distribution (herein called morning-type and evening-type individuals) gave informed consent, and received course credit or $40 CAD to participate in the experiment. Data from 4 morning types and 14 evening types were discarded due to excessive ocular artifacts (n = 9), failure to complete experiment (n = 7), or insufficient sleep (< 60 min) prior to a session (n = 2). Of the remaining participants, 23 were characterized as evening types (16 women, mean age = 19.7 years, 18 right-handed; MSF = 7:42 AM; range = 6:33– 10:05 AM) and 23 were characterized as morning types (18 women, mean age = 20.6, all right-handed; MSF = 4:25 AM; range = 2:40–5:07 AM). All subjects reported normal or corrected-to-normal visual acuity and had normal colour vision. The sample size was chosen in advance based on prior studies in our lab showing moderate effect sizes.

Stimuli and Procedure

Participants completed a questionnaire about the quality and duration of sleep from the preceding night at the beginning of each experimental session and reported their level of sleepiness and alertness (on analog scales) before and after completing each session.

Participants were trained to search for a yellow target that was accompanied by seven green disks (nontargets) or by six green disks and one red disk while maintaining eye fixation on a centrally presented cross (Figure 1). The red disk (herein called the distractor) was perceived to be more salient than the yellow target in part because the distance in chromaticity space between red and green is greater than that between yellow and green (Gaspar et al., 2016; Smith & Guild, 1931). Each of the eight disks contained a horizontal or vertical line segment, and participants were required to press one of two response buttons depending on the orientation of the line within the yellow disk.

All stimuli were presented at 7–9 cd/m^2 on an otherwise black background (0.5 cd/m^2). The eight unfilled disks were presented equidistant (9.2°) from a central fixation point. Each disk was 3.4° in diameter with a 0.3° thick outline. Yellow (x = 0.42, y = 0.52), red (x = 0.64, y = 0.32), and green (x = 0.29, y = 0.64) disks served as target, distractor, and nontargets, respectively. Distractor-absent displays (33.4%) consisted of seven nontargets and one target, whereas distractor-present displays (66.6%) consisted of six nontargets, one target, and one distractor. A horizontal or vertical gray line (x = 0.30, y = 0.36) was positioned within each of the disks, with orientation determined randomly and independently

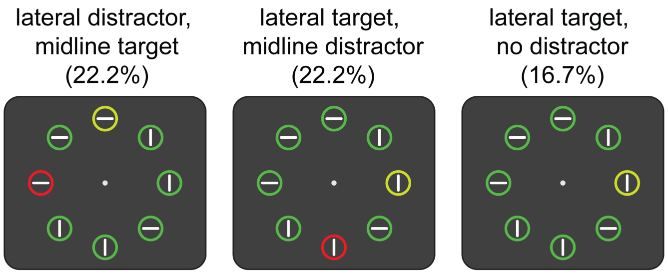

Figure 1. Example stimulus displays showing relative locations of the target (yellow disk) and distractor (red disk).

for each position. A grey, lower-case “x” was used as an indicator that a search array would appear.

Each trial began with an 800–1,200 ms fixation period, during which only the central fixation point was presented. After the period, the x-indicator was presented for 100 ms. The search display was presented 900 ms after the onset of the x-indicator and lasted until 100 ms after a button-press response was registered. Participants were instructed to maintain fixation on the central point and to identify the orientation of the gray line inside the target singleton by pressing one of two response buttons on a computer mouse as quickly as possible. Participants were also told to remain still and to avoid excessive blinking throughout each block of trials and to time blinks with the onset of the x-indicator when needed.

Target and distractor locations were varied to produce the following display configurations: Lateral target with no distractor (16.7%); midline target with no distractor (16.7%); midline target with midline distractor (11.1%), lateral target with contralateral distractor (11.1%); lateral target with midline distractor (22.2%); lateral distractor with midline target (22.2%). Different display configurations were randomly intermixed within each block of trials. Each experimental block comprised 36 trials. At the end of the block, participants were given a minimum 5-s rest period and were permitted to begin the next block whenever they decided. Each session contained 32 blocks, for a total of 1152 trials per participant. At least 36 practice trials were given to each participant prior to the start of each session. The order of the morning (9 AM) and afternoon (4 PM) sessions was counterbalanced across participants, separately for each chronotype. Each session lasted approximately 2 hours.

Behaviour

Median reaction times (RTs) were derived for distractor-present and distractor-absent trials for each participant. Trials on which the participant responded incorrectly, too quickly (RT < 300 ms) or too slowly (RT > 1,500 ms) were excluded from all behavioural and ERP analyses. Trials contaminated by ocular artifacts were also rejected from the behavioural analysis. After artifact rejection, the median RTs were averaged across participants separately for each of the four combinations of chronotype (morning, evening) and session time (9 AM, 4 PM). Distractor interference was assessed by comparing the overall RTs obtained on distractor present trials and distractor absent trials. Group differences were assessed statistically using an ANOVA with a within-subjects factor for session time and a between-subjects factor for chronotype.

Electrophysiology

EEG signals were recorded from active sintered Ag-AgCl electrodes from 32 electrodes. An additional pair of electrodes placed 1 cm lateral to the external canthus of each eye was used to monitor the horizontal EOG. All EEG and EOG signals were digitized at 512 Hz, referenced in real time to an active common-mode electrode, and low-pass filtered using a fifth-order sinc filter with a half-amplitude cutoff at 104 Hz. After acquisition, EEG signals were high-pass filtered (half-amplitude cutoff at 0.05 Hz) and then converted from 24-bit to 12-bit integers. Artifact-free epochs associated with two display configurations of interest were then averaged separately to create ERP waveforms. The resulting ERPs were digitally low-pass filtered (half-amplitude cutoff at 32 Hz) to remove high-frequency noise and were digitally re-referenced to the average of the left and right mastoids.

For each participant, ERPs to the search displays were collapsed across left and right visual hemifields, as well as left and right electrodes to produce waveforms recorded contralateral and ipsilateral to a lateralized singleton. Difference waveforms were then computed for each display configuration of interest by subtracting the ipsilateral waveform from the corresponding contralateral waveform at electrode sites P07 and P08. Negative voltages were plotted upward so that the N2pc would appear in these difference waveforms as an upward deflection and the P_D as a downward deflection.

Lateral-distractor-with-midline-target displays

The magnitudes of the distractor-elicited P_D and N2pc components were quantified as the signed positive or negative area under the contralateral-ipsilateral difference waveform within pre-specified time windows. The P_D was measured within a 125 ms time window beginning 175 ms after display onset, while the distractor-elicited N2pc was measured within a 75 ms time window beginning 150 ms after display onset. These specific area-measurement windows were selected based on the onset latencies and durations of P_D and N2pc in recent studies (Gaspar et al., 2016; Gaspar & McDonald, 2014, 2018). Because signed area measures are inherently biased to be non-zero and sensitive to the amount of noise in the signal (Sawaki, Geng, & Luck, 2012), we used our standard procedure of subtracting signed (positive or negative) noise area from equal-width pre-stimulus baseline intervals (with end-of-interval at display onset) and then performed all statistical tests on the adjusted area measures (Gaspar et al., 2016).

Lateral-target-with-midline-distractor displays

The magnitudes of the target-elicited N2pc components were quantified as the signed negative area within a 200 ms interval starting 200 ms after display onset.

Experimental Design and Statistical Analysis

Statistical tests were performed as two-tailed tests except where noted. Variations in each ERP measure were evaluated separately within each group because our main a priori hypotheses concerned the evening chronotypes. There were two main sets of analyses. The first set tested for differences in the magnitude of each ERP component (P_D, distractor N2pc, target N2pc) across the two testing sessions. For the evening-type group, the P_D and distractor-elicited N2pc tests were performed as one-tailed tests because (i) the predicted effects were directional (P_D was predicted to be smaller in the morning than in the afternoon; distractor N2pc was predicted to be larger in the morning than in the afternoon), and (ii) reverse effects (e.g., smaller P_D in the afternoon than in morning) would not be interpreted. A second set of tests was done to assess the presence or absence of each component in each session. Specifically, a one-sample t-test was conducted for each combination of chronotype and session to determine whether the adjusted area for that component (P_D, distractor N2pc, target N2pc) was different than zero. Because tests of signed area (vs. the null) are inherently directional (e.g., the signed positive area of the P_D was predicted to be more positive than zero), these tests were one-tailed. Cohens *d* effect sizes are reported for significant results.

Sleep loss comparisons

To test whether differences in electrophysiological responses were due to misaligned circadian time per se, and not resultant sleep loss in evening type individuals forced to show up for an early testing time, we created sleep-equalized subgroups within our evening and morning type samples. Habitual sleep durations were calculated by using the data from original pre-screening MCTQ responses, and sleep loss percentages were calculated by comparing subjects' reported sleep duration from the night prior to test day. We sequentially removed, as pairs, the most sleep deprived evening types and least sleep deprived morning types until the average sleep reduction (compared to free day sleep durations) between both chronotype groups was within 1% (70.7% and 70.1% of free-day sleep for morning and evening types respectively).

Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Results

Morning Chronotypes

Figure 2 illustrates the main electrophysiological results from the morning chronotypes, who were predicted to perform equally well in the two testing sessions. When the distractor was on the midline, a

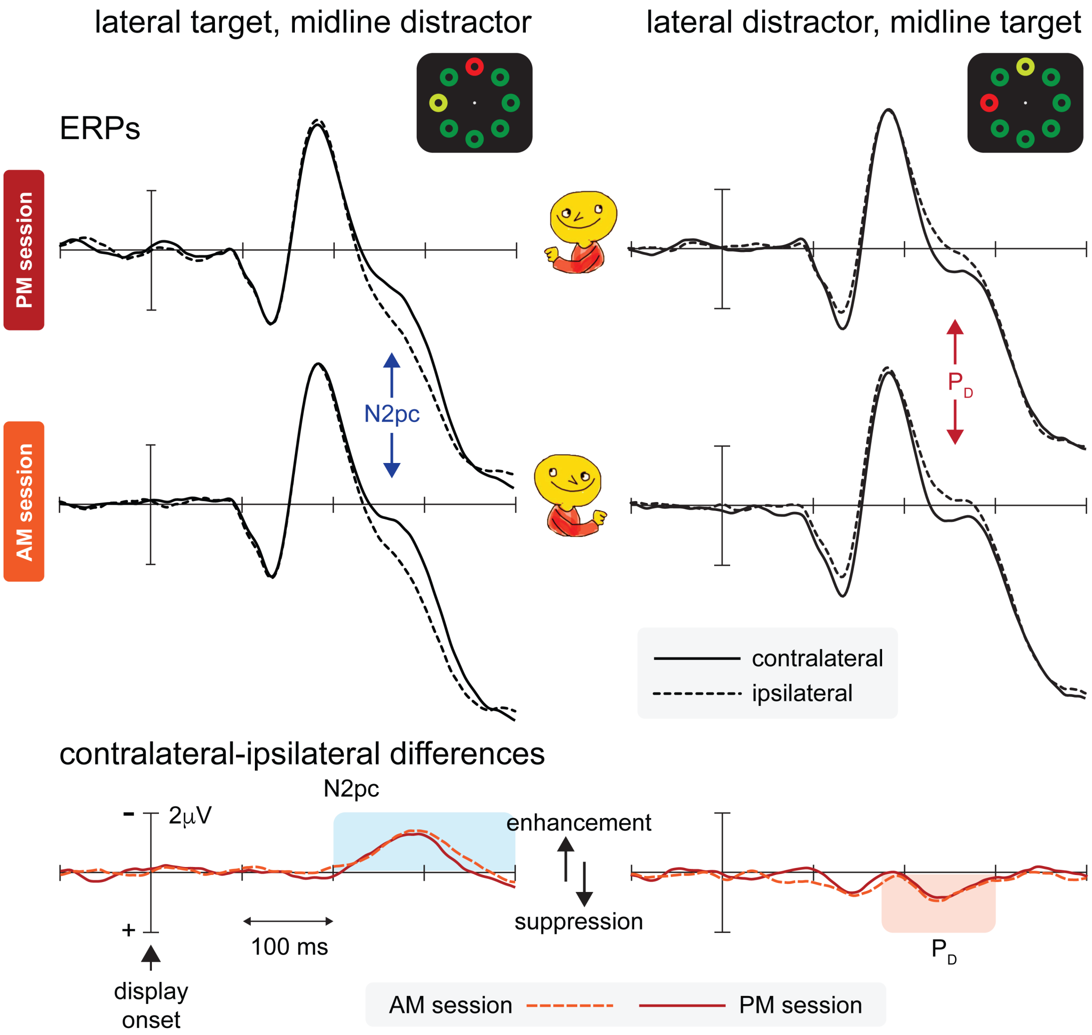

Figure 2. Electrophysiological results for the morning chronotypes. The left column shows grand-averaged ERPs recorded contralateral and ipsilateral to the target (with distractor on vertical midline), separately for the morning and afternoon sessions. The right column shows grand-averaged ERPs recorded contralateral and ipsilateral to the distractor (with target on vertical midline), separately for the morning and afternoon sessions. The N2pc and P_D appear as differences between the contralateral and ipsilateral waveforms. Contralateral-minus-ipsilateral difference waveforms are plotted below the ERPs to show N2pc and P_D as upward and downward deflections, respectively. Shaded boxes represent the measurement windows for the target-elicited N2pc (blue) and distractor-elicited P_D (in red). Negative voltages are plotted upwards.

lateral target was found to elicit an N2pc in each testing session [one-sample t-tests vs. zero: each $t(22) > 4.65$, each $P < .001$, each $d > 0.97$]. Conversely, when the target was on the midline, a lateral distractor was found to elicit a P_D in each testing session [one-sample t-tests: each $t(22) > 4.03$, each $P < .001$, each *d* > 0.84]. Neither the target-elicited N2pc nor the distractor-elicited P_D varied significantly across sessions [N2pc: t(22) = 1.21, *P* = 0.24; P_D: t(22) = .078, *P* = 0.94]. As predicted, these results demonstrate that morning chronotypes are able to selectively attend to the target and to suppress the distractor in the beginning and end of a typical work day.

Evening Chronotypes

Figure 3 illustrates the main electrophysiological results from the evening chronotypes, who were predicted to have an inhibitory control deficit in the morning session. When the distractor appeared on the midline, a lateral target was found to elicit an N2pc in the morning session [one-sample t-test: *t*(22) = 3.80 , *P* = .001, *d* = 0.79] as well as in the afternoon session [one-sample t-test: *t*(22) = 4.57, *P* = .000, *d* = 0.95]. This target N2pc did not differ significantly between sessions [paired t-test: *t*(22) = 1.61, *P* = .123] demonstrating an ability to search for visual targets.

The right column of Figure 3 shows the ERPs elicited by displays containing a lateral distractor and a midline target, averaged across the evening chronotypes in each session. Unlike the morning chronotypes, who managed to suppress the distractor in both sessions, the evening chronotypes showed the two predicted signs of an inhibitory control deficit in the morning session. First, although the P_D was present in both sessions [one-sample t-tests; morning: *t*(22) = 2.87, *P* = .009, *d* = 0.60; afternoon: *t*(22) = 3.32, *P* = .003, *d* = 0.69], the distractor elicited a significantly smaller P_D in the morning than in the afternoon [paired t-test, one-tailed: *t*(22) = 1.85, *P* = .039, *d* = 0.39]. Second, the distractor was found to elicit an N2pc in the morning session [one-sample t-test: *t*(22) = 2.16, *P* = .042, *d* = 0.45] but not in the afternoon session [one-sample t-test: *t*(22) = 1.41, *P* = .171]. Together, these findings show that evening chronotypes were unable to suppress the distractor in time to prevent that item from capturing attention.

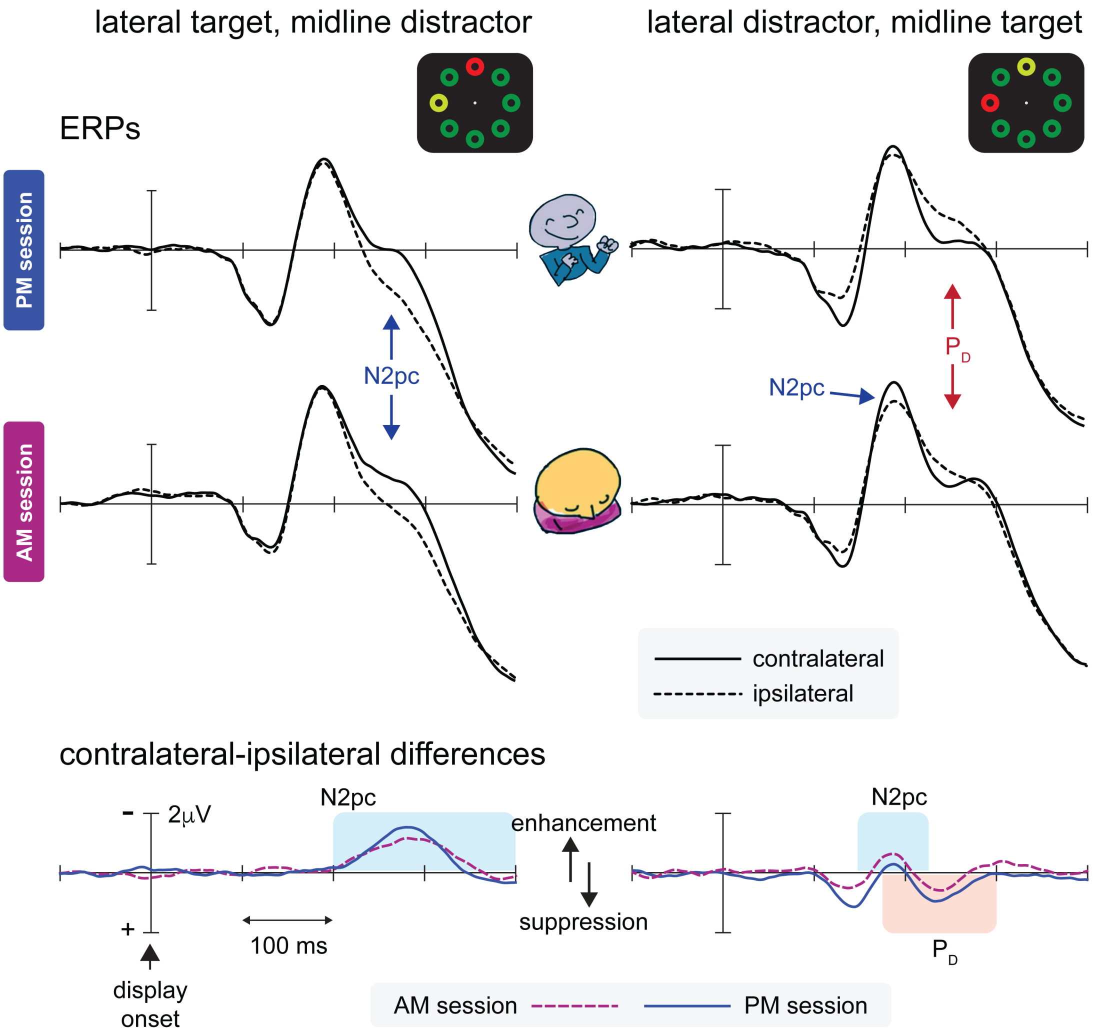

Figure 3. Electrophysiological results for the evening chronotypes. The left column shows grand-averaged ERPs recorded contralateral and ipsilateral to the target (with distractor on vertical midline), separately for the morning and afternoon sessions. The right column shows grand-averaged ERPs recorded contralateral and ipsilateral to the distractor (with target on vertical midline), separately for the morning and afternoon sessions. Contralateral-minus-ipsilateral difference waveforms are plotted below the ERPs to show N2pc and P_D as upward and downward deflections, respectively. Shaded boxes represent the measurement windows for the target- and distractor-elicited N2pc components (blue) and the P_D (in red). Negative voltages are plotted upwards.

Behavioural Results

Examination of mean reaction times underscores the importance of looking at neurophysiological measures of processing rather than relying on indirect behavioural measures. Participants were coached to perform as fast as possible, while maintaining accuracy. Behaviourally, the presence of the distractor did little to slow responses (Figure 4), as mean response times were only 4 ms longer on distractor-present trials than on distractor-absent trials (613 ms vs. 609 ms, respectively). In an ANOVA with within-subject factors for distractor presence (present, absent) and session time (AM, PM) and a between-subject factor for chronotype (morning, evening), only the main effect of distractor presence was significant [*F*(1,44) = 11.25, *P* = .002; chronotype main effect approached significance: *F*(1,44) = 2.69, *P* = .108]. This indicates that although evening types were unable to completely ignore the distractor in the morning session (as evidenced by the distractor-elicited N2pc), processing of the distractor did little to impact target processing in the present task.

Sleep Loss comparison groups

Both chronotype groups reported sleeping less prior to morning sessions than evening sessions, but the difference was considerably greater for evening types. Compared to free days, evening types reported sleeping 38% less and 18% less during nights that preceded the morning and afternoon sessions, respectively, whereas morning-type participants reported sleep reductions of approximately half that magnitude (20% and 11%, respectively). The attention deficit in morning sessions may reflect

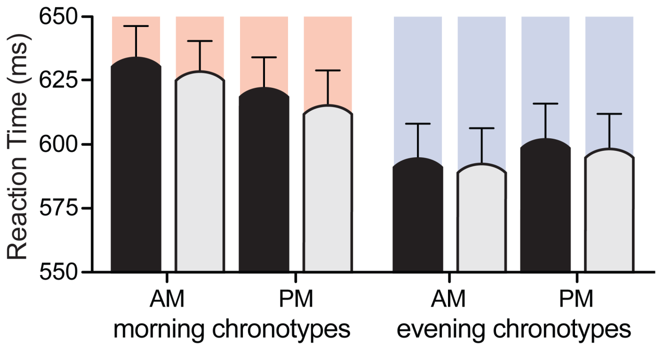

Figure 4. Mean response times on distractor-present trials (black bars) and distractor-absent trials (grey bars) for Morning Types (left) and Evening Types (right). Error bars denote standard errors of the means.

the non-optimal testing time for evening types, their greater sleep deficit, or an interaction between both factors. Although other experimental protocols (e.g., forced desynchrony) would be required to separate and quantify the relative contributions of circadian phase and prior sleep duration to the distractor-suppression deficit. First, self-report subjective sleepiness ratings (done on an analogue scale) did not differentiate evening and morning types at the 9 AM testing session [$t(44) = 0.15$, $P = .440$]. Second, similar signs of inhibitory control deficit were observed for the evening-type participants relative to the morning-type participants when subsets ($n = 16$) from the two groups were equated for sleep lost prior to 9 AM testing [one-tailed unpaired-samples t-tests: distractor N2pc: $t(30) = 1.51$, $P = .071$, $d = 0.53$; P_D: $t(30) = 1.61$, $P = .060$, $d = 0.57$] and when the full samples were compared [distractor N2pc: $t(44) = 1.82$, $P = .038$, $d = 0.57$; P_D: $t(44) = 2.17$, $P = .018$, $d = 0.64$], although the differences between the sleep-equated groups were only marginally significant due to a loss of statistical power (Figure 5).

Discussion

The electrophysiological findings from the present study show that evening-type individuals managed to suppress a salient visual distractor in an afternoon testing session, as evidenced by a P_D, but were less able to suppress the distractor in a morning testing session, as evidenced by an attenuated P_D and a concomitant distractor-elicited N2pc. These results indicate that failure to filter out irrelevant stimuli at an early stage of perceptual processing contributes to impaired cognitive functioning at non-optimal times of day, and may underlie real-world performance impairments associated with circadian mismatch. Morning chronotypes did not show this deficit at either the 9 AM or 4 PM test time. It is presumed that we would see similar deficits for morning types late in the day, at a time closer to their circadian trough, however, we chose the afternoon test time for ecological validity relating to the traditional work day.

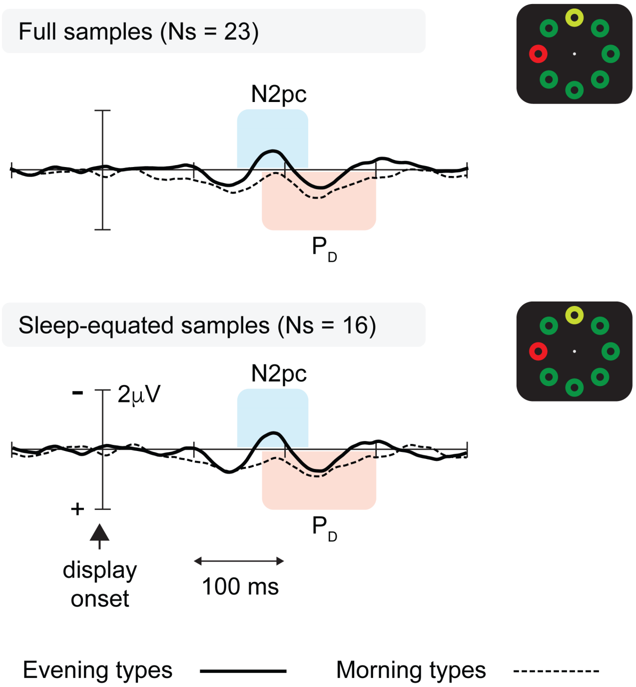

Figure 5. Comparison of distractor-elicited N2pc (150 - 225 ms) and P_D (200 - 400 ms) contralateral-ipsilateral difference waves at 9AM testing time, between morning and evening types, for the full sample and sleep-equalized subsets. The top panel shows a comparison of the difference waves for full data sets (n = 23 per group) of both morning (dashed black line) and evening types (solid black line). The bottom panel shows a comparison of the same data for subsets (n = 16 per group) of morning (dashed blue line) and evening types (solid blue line) that have been equalized for sleep loss on the morning test day by removing the most sleep deprived evening types and the least sleep deprived morning types.

As evidenced by the unfettered target-elicited N2pc, participants did retain the ability to search for a unique-colour target that appeared with a more salient distractor. These findings fit well with existing evidence that healthy individuals retain the ability to search for visual targets when there is substantial misalignment between their optimal circadian time and the time of testing. In prior studies, participants retained the ability to search for targets that were defined by specific conjunctions of features (e.g., red vertical bar appearing among red horizontal and green vertical bars) and for targets that were mirror-images of the nontargets (e.g., digital 2 among digital 5s; Horowitz et al., 2003).

The present study demonstrates that healthy evening-type adults have a specific attention deficit—a reduced ability to suppress salient-but-irrelevant visual objects—in the early part of a typical work day. While none of our participants had been diagnosed with ADHD, their early-morning suppression bears some similarity to the inattentiveness that defines one of the three main types of ADHD (American Psychiatric Association, 2013). Like our evening chronotypes, children with ADHD have difficulty suppressing salient visual distractors, as evidenced by a reduced-amplitude P_D compared to typically developing children (Wang et al., 2016). Notably, however, the distractor-suppression deficit observed here was present only in the morning session, which began closer to the circadian trough of many evening-type individuals. Thus, we conclude that misalignment between circadian time and performance time leads to an ADHD-like deficit in inhibitory attentional control that manifests as an inability to ignore salient visual distractors, at least for evening chronotypes.

Interestingly, the inhibitory-control deficit revealed by our neurophysiological measures was not associated with a behavioural deficit. The absence of a behavioural impairment was unsurprising and likely due to several factors. First, recent research has shown that people can attend to up to three or four items simultaneously (Eimer & Grubert, 2014; Ester, Drew, Klee, Vogel, & Awh, 2012; Mazza & Caramazza, 2011), at least in simple tasks. Thus, in an easy laboratory computer task, attending to a distractor does not necessarily prevent rapid selection of a target. Second, the spatial separation between target and distractor is known to affect the amount of behavioural interference (i.e. slowing of response times) that occurs in tasks like the one used here (Jannati, Gaspar, & McDonald, 2013; Gaspar & McDonald, 2014; Mounts, 2000). Specifically, behavioural interference is maximal when the distractor is immediately adjacent to the target (i.e. no intervening nontargets) and is minimal when the distractor is on the opposite side of the display (i.e visually farther away from the target). In the present study, the distractor was always spatially separated from the target by at least one intervening nontarget, which would have reduced interference. This was done to better isolate lateralized ERP activities associated with target and distractor processing. In other words, the display configurations used in the present study may have reduced behavioural interference but enabled us to better isolate the distractor-elicited N2pc and (reduced) P_D. As such, the absence of behavioural deficit may not extend to more complex real-world scenarios. The present results provide evidence that an attention deficit is present for evening types in the morning at an early stage of perceptual processing, however further investigation is warranted to determine if behavioural deficits are only expressed in more complex scenarios, or if compensatory mechanisms are utilized during later stages of processing to help protect against time of day effects.

The results of the present study have implications for cognitive and neuroscience studies that rely wholly or in part on the participation of undergraduate students. There is a high prevalence of moderate-to-extreme evening chronotypes in most university settings due to a delay in circadian phase at the average age of the typical undergraduate student body (Roenneberg et al., 2004). Consequently, most investigators should probably avoid scheduling experiments to be run in the early morning, particularly if the experimental task taps into inhibitory control processes (including, but not limited to studies of attention and working memory). A more comprehensive plan would be to assess each participant's chronotype and to run each participant at their optimal testing times.

The morning and afternoon testing times used in the present study correspond to the start and end of typical work or school days. The fact that an inhibitory control deficit was evident at 9 AM has implications for health and safety as well as for optimal learning and productivity. In terms of health and safety, the present results suggest that a substantial proportion of young adults make their way to school and to the workplace at a time when their ability to avoid distraction is compromised. Delaying the start of the work day by several hours, or adopting a more flexible schedule that could be matched to individual biological rhythms may significantly reduce the incidence of accidents at work and on the morning commute (Wheaton, Chapman, & Croft, 2016). In terms of optimal learning, our findings implicate that an early-morning attention deficit may contribute to learning disability and low scholastic performance at schools and universities. Thus, delaying the start of the school day may better enable adolescent students—many of whom are moderate to extreme evening chronotypes (Roenneberg et al., 2004)— to learn optimally throughout the school day and to achieve better academic success as a result (Wheaton, Chapman, & Croft, 2016).

References

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)*. American Psychiatric Pub.

Burke, T. M., Scheer, F. A., Ronda, J. M., Czeisler, C. A., & Wright Jr, K. P. (2015). Sleep inertia, sleep homeostatic and circadian influences on higher-order cognitive functions. *Journal of sleep research*, *24*(4), 364-371.

Chellappa, S. L., Morris, C. J., & Scheer, F. A. (2018). Daily circadian misalignment impairs human cognitive performance task-dependently. *Scientific reports*, *8*(1), 3041.

Czeisler, C. A., & Dijk, D. J. (2001). Human circadian physiology and sleep-wake regulation. In Takahashi, J.S., Turek, F.W. & Moore, R.Y (Eds.), *Circadian clocks* (pp. 531-569). Boston, MA: Springer.

Duffy, J. F., Rimmer, D. W., & Czeisler, C. A. (2001). Association of intrinsic circadian period with morningness–eveningness, usual wake time, and circadian phase. *Behavioral neuroscience*, *115*(4), 895.

Duffy, J. F., Dijk, D. J., Hall, E. F., & Czeisler, C. A. (1999). Relationship of endogenous circadian melatonin and temperature rhythms to self-reported preference for morning or evening activity in young and older people. *Journal of investigative medicine: the official publication of the American Federation for Clinical Research*, *47*(3), 141-150.

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology*, *24*(2), 193-198.

Engle, R. W. (2002). Working memory capacity as executive attention. *Current directions in psychological science*, *11*(1), 19-23.

Ester, E. F., Drew, T., Klee, D., Vogel, E. K., & Awh, E. (2012). Neural measures reveal a fixed item limit in subitizing. *Journal of Neuroscience*, *32*(21), 7169-7177.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: attentional control theory. *Emotion*, *7*(2), 336.

Gaspar, J. M., Christie, G. J., Prime, D. J., Jolicœur, P., & McDonald, J. J. (2016). Inability to suppress salient distractors predicts low visual working memory capacity. *Proceedings of the National Academy of Sciences*, *113*(13), 3693-3698.

Gaspar, J. M., & McDonald, J. J. (2014). Suppression of salient objects prevents distraction in visual search. *Journal of neuroscience*, *34*(16), 5658-5666.

Gaspar, J. M., & McDonald, J. J. (2018). High Level of Trait Anxiety Leads to Salience-Driven Distraction and Compensation. *Psychological science*, *29*(12), 2020-2030.

Gazzaley, A., Cooney, J. W., Rissman, J., & D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature neuroscience*, *8*(10), 1298.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age. Gopher, D. & Koriat, A. (Eds.), In *Attention and performance XVII: Cognitive regulation of performance: Interaction of theory and application* (653–675). Cambridge, MA: MIT Press.

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of cognitive neuroscience*, *21*(4), 760-775.

Hida, A., Kitamura, S., Ohsawa, Y., Enomoto, M., Katayose, Y., Motomura, Y., ... & Higuchi, S. (2013). In vitro circadian period is associated with circadian/sleep preference. *Scientific reports*, *3*, 2074.

Horowitz, T. S., Cade, B. E., Wolfe, J. M., & Czeisler, C. A. (2003). Searching night and day: a dissociation of effects of circadian phase and time awake on visual selective attention and vigilance. *Psychological Science*, *14*(6), 549-557.

Jannati, A., Gaspar, J. M., & McDonald, J. J. (2013). Tracking target and distractor processing in fixed-feature visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(6), 1713.

Kerkhof, G. A., & Van Dongen, H. P. (1996). Morning-type and evening-type individuals differ in the phase position of their endogenous circadian oscillator. *Neuroscience letters*, *218*(3), 153-156.

Logan, G. D., Schachar, R. J., & Tannock, R. (1997). Impulsivity and inhibitory control. *Psychological science*, *8*(1), 60-64.

Luck, S. J., & Hillyard, S. A. (1994). Electrophysiological correlates of feature analysis during visual search. *Psychophysiology*, *31*(3), 291-308.

Luck, S. J. (2012). Electrophysiological correlates of the focusing of attention within complex visual scenes: N2pc and related ERP components. In Luck, S. J. & Kappenman, E. S. (Eds.), *The Oxford handbook of event-related potential components*, 329-360. Oxford: Oxford University Press

Mazza, V., & Caramazza, A. (2011). Temporal brain dynamics of multiple object processing: the flexibility of individuation. *PloS one*, *6*(2), e17453.

Mounts, J. R. (2000). Attentional capture by abrupt onsets and feature singletons produces inhibitory surrounds. *Perception & Psychophysics*, *62*(7), 1485-1493.

Roenneberg, T., Kuehnle, T., Pramstaller, P. P., Ricken, J., Havel, M., Guth, A., & Merrow, M. (2004). A marker for the end of adolescence. *Current Biology*, *14*(24), R1038-R1039.

Roenneberg, T., Wirz-Justice, A., & Merrow, M. (2003). Life between clocks: daily temporal patterns of human chronotypes. *Journal of biological rhythms*, *18*(1), 80-90.

Sawaki, R., Geng, J. J., & Luck, S. J. (2012). A common neural mechanism for preventing and terminating the allocation of attention. *Journal of Neuroscience*, *32*(31), 10725-10736.

Schmidt, C., Collette, F., Cajochen, C., & Peigneux, P. (2007). A time to think: circadian rhythms in human cognition. *Cognitive neuropsychology*, *24*(7), 755-789.

Smith, T., & Guild, J. (1931). The CIE colorimetric standards and their use. *Transactions of the optical society*, *33*(3), 73.

Wang, E., Sun, L., Sun, M., Huang, J., Tao, Y., Zhao, X., ... & Wang, Y. (2016). Attentional selection and suppression in children with attention-deficit/hyperactivity disorder. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *1*(4), 372-380.

Woodman, G. F., & Luck, S. J. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *29*(1), 121.

Wheaton, A. G., Chapman, D. P., & Croft, J. B. (2016). School start times, sleep, behavioral, health, and academic outcomes: a review of the literature. *Journal of School Health*, *86*(5), 363-381.

Author Notes

Acknowledgments This study was supported by the Natural Sciences and Research Council of Canada (to R.E.M. and J.J.M.), Canadian Foundation for Innovation (to J.J.M.), and the Canada Research Chairs program (to J.J.M.).

Author Contributions A.C.L., A.N.S., M.J.M., R.E.M., and J.J.M. designed the experiments; A.C.L., A.N.S., and M.J.M. performed the experiments and analyzed the data; J.J.M., A.N.S., M.J.M., and R.E.M. wrote the manuscript. The first two authors shared first-author responsibilities equally, and order of these two authors was determined by a race up Vancouver's Grouse Grind trail.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing interest. Correspondence and requests for materials should be addressed to J.J.M. (jmcd@sfu.ca).

Figure Captions

Figure 1. Example stimulus displays showing relative locations of the target (yellow disk) and distractor (red disk).

Figure 2. Electrophysiological results for the morning chronotypes. The left column shows grand-averaged ERPs recorded contralateral and ipsilateral to the target (with distractor on vertical midline), separately for the morning and afternoon sessions. The right column shows grand-averaged ERPs recorded contralateral and ipsilateral to the distractor (with target on vertical midline), separately for the morning and afternoon sessions. The N2pc and P_D appear as differences between the contralateral and ipsilateral waveforms. Contralateral-minus-ipsilateral difference waveforms are plotted below the ERPs to show N2pc and P_D as upward and downward deflections, respectively. Shaded boxes represent the measurement windows for the target-elicited N2pc (blue) and distractor-elicited P_D (in red). Negative voltages are plotted upwards.

Figure 3. Electrophysiological results for the evening chronotypes. The left column shows grand-averaged ERPs recorded contralateral and ipsilateral to the target (with distractor on vertical midline), separately for the morning and afternoon sessions. The right column shows grand-averaged ERPs recorded contralateral and ipsilateral to the distractor (with target on vertical midline), separately for the morning and afternoon sessions. Contralateral-minus-ipsilateral difference waveforms are plotted below the ERPs to show N2pc and P_D as upward and downward deflections, respectively. Shaded boxes represent the measurement windows for the target- and distractor-elicited N2pc components (blue) and the P_D (in red). Negative voltages are plotted upwards.

Figure 4. Mean response times on distractor-present trials (black bars) and distractor-absent trials (grey bars) for Morning Types (left) and Evening Types (right). Error bars denote standard errors of the means.

Figure 5. Comparison of distractor-elicited N2pc (150 - 225 ms) and P_D (200 - 400 ms) contralateral-ipsilateral difference waves at 9AM testing time, between morning and evening types, for the full sample and sleep-equalized subsets. The top panel shows a comparison of the difference waves for full data sets (n = 23 per group) of both morning (dashed black line) and evening types (solid black line). The bottom panel shows a comparison of the same data for subsets (n = 16 per group) of morning (dashed blue line) and evening types (solid blue line) that have been equalized for sleep loss on the morning test day by removing the most sleep deprived evening types and the least sleep deprived morning types.