

## Sleep duration, sleep variability, and impairments of visual attention

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# Sleep duration ~~and~~, sleep variability, ~~predict~~ and impairments ~~in~~ of visual attention

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# Sleep duration, ~~sleep~~ and variability, and impairments predict impairments ~~in~~of visual attention

## Abstract

Attentional networks are sensitive to sleep deprivation. However, variation in attentional performance as a function of normal sleep parameters is under-studied. We examined whether attentional performance is influenced by 1) individual differences in sleep duration; 2) sleep duration variability; and/or 3) their interaction. Fifty-seven healthy participants (61.4% female; mean age=32.37 years; SD=8.68) completed questionnaires, wore wrist actigraphy for one week, and subsequently completed the Attention Network Test. Sleep duration and sleep duration variability did not predict orienting score, executive control score or error rates. Sleep duration variability appeared to moderate the association between sleep duration with overall reaction time ( $\beta = -.34$ ,  $t = -2.13$ ,  $p = .04$ ) and alerting scores ( $\beta = -.43$ ,  $t = 2.94$ ,  $p = .01$ ), though further inspection of the data suggested that these were spurious findings. Time of testing was a significant predictor of alerting score ( $\beta = .35$ ,  $t = 2.96$ ,  $p = .01$ ), chronotype of orienting ( $\beta = .31$ ,  $t = 2.28$ ,  $p = .03$ ) and age of overall reaction time ( $\beta = .35$ ,  $t = 2.70$ ,  $p = .01$ ). Our results highlight the importance of examining the associations between variations in sleep-wake patterns and attentional networks in samples with greater variation in sleep, as well as the importance of rigorously teasing apart mechanisms of the sleep homeostat from those related to the circadian rhythm in studies examining cognition.

## Keywords

Attention, Cognition, Sleep Deprivation, Sleep Duration, Sleep Variability

## Introduction

Insufficient sleep, in either quantity or quality, initiates a cascade of physiological events, which alter brain neurochemistry, and in consequence – our health and behaviour. Perhaps one of the most noticeable consequences of insufficient sleep is the inability to successfully focus attention and maintain an alert state. Numerous studies have highlighted the detrimental effects of experimentally induced sleep restriction or total sleep deprivation on vigilant attention (Basner & Dinges, 2011; Basner, Mollicone, & Dinges, 2011; Lim & Dinges, 2008); while other studies show that response speeds decrease in a dose-response manner as sleep duration decreases (Belenky et al., 2003; Van Dongen, Maislin, Mullington, & Dinges, 2003).

Some reports suggest that contemporary society imposes a state of chronic sleep deprivation in the Western world (Webb & Agnew, 1975). Today it is common to impose restrictions on our sleep to optimise our time spent awake, but this comes at a cost to our health, mood, occupational safety, and cognition (Cappuccio, D'Elia, Strazzullo, & Miller, 2010; Fernandez-Mendoza et al., 2010; Kalmbach, Arnedt, Song, Guille, & Sen, 2017). An epidemiological study demonstrated that the typical sleep duration of young adults during weekdays is around 6.7 hours (Breslau, Roth, Rosenthal, & Andreski, 1997), which is below the 8 hours recommended for this age group (Hirshkowitz et al., 2015). In addition to suboptimal sleep duration, adherence to consistent and biologically compatible sleep schedules are often impinged by external environmental factors such as work commitments, social engagements and 24/7 electronic stimulation (Wittmann, Dinich, Mellow, & Roenneberg, 2006). Indeed, it is common to see a mismatch between sleep obtained on work-days and that obtained on free-days, which is indicative of a state of “social jetlag”, imposed by our social world (Wittmann et al., 2006). On work-days, constrained sleep offset times often result in drastically curtailed sleep duration - a sleep “debt” that is paid off on free-days

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3 by extending sleep where the opportunity permits. However, employing compensatory  
4 behaviours, such as extension of time in bed on free-days, and going to bed earlier than what  
5 would be dictated by the endogenous circadian rhythm on work-days, is maladaptive (Buysse  
6 et al., 2010). This coupling of short sleep duration and self-imposed variability in sleep  
7 behaviours may disrupt the homeostatic drive for sleep, making it difficult to get to sleep  
8 when desired, and potentially contributing to a delayed circadian phase. Consequently, we  
9 may develop a sleep schedule at conflict with the constraints of the social world.  
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20 Several studies have shown that intra-individual variability in sleep duration is often  
21 greater than that observed between individuals (Knutson, Rathouz, Yan, Liu, & Lauderdale,  
22 2007; Tworoger, Lee, Schernhammer, & Grodstein, 2006) and it is possible that sleep  
23 duration variability contributes to the development or maintenance of sleep disorders  
24 (Billiard, Alperovitch, Perot, & Jammes, 1987; Buysse et al., 2010; Spielman, Caruso, &  
25 Glovinsky, 1987). Indeed, individuals with insomnia often experience night-to-night  
26 variability across various domains assessed subjectively by sleep diaries, and objectively – by  
27 actigraphy (Buysse et al., 2010; Vallières, Ivers, Bastien, Beaulieu-Bonneau, & Morin, 2005;  
28 Vallières, Ivers, Beaulieu-Bonneau, & Morin, 2011). Difficulty sleeping on one night may  
29 increase sleep pressure such that the subsequent sleep period is longer, deeper and more  
30 restorative. In some cases, several nights of poor sleep may be followed by a night of  
31 relatively good sleep (Vallières et al., 2005; Vallières et al., 2011), though this pattern is not  
32 predictably consistent (Buysse et al., 2010).  
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50 Whilst most research on the consequences of insufficient sleep have focussed on short  
51 sleep duration or sleep disruption, the importance of *consistent sleep schedules* is often  
52 overlooked. Sleep variability has been broadly defined as inconsistencies in various sleep  
53 indices including sleep onset and offset timing, sleep latency, sleep quality, wake after sleep  
54 onset, sleep duration and efficiency. It is typically calculated as the variability from weekdays  
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3 to weekends (Lemola, Schwarz, & Siffert, 2012), or as the within-subject standard deviation  
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5 for the corresponding variables over the course of several days (Whiting & Murdock, 2016)  
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7 to weeks (Lemola, Ledermann, & Friedman, 2013; Lev Ari & Shulman, 2012;  
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9 Sánchez-Ortuño & Edinger, 2012).

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13 Greater sleep variability has been negatively associated with health (e.g. higher body  
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15 mass index: Moore et al., 2011), mood (e.g. poorer subjective well-being: Lemola et al.,  
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17 2013; and increased severity of depression: Suh et al., 2012), and behaviour (e.g. adolescent  
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19 aggression: Lemola et al., 2012). Of particular relevance to the current study, Whiting and  
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21 Murdock (2016) demonstrated that sleep duration variability moderates the association  
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23 between sleep duration and attentional disengagement; i.e., the capacity to withdraw attention  
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25 from the currently focused stimulus (attentional switch). Shorter sleep duration was  
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27 associated with poorer ability to switch attention when coupled with low sleep duration  
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29 variability. Therefore, consistently short sleep duration was associated with greatest deficits  
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31 in attentional disengagement, and consistently longer sleep duration was associated with  
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33 better performance.  
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40 The majority of work on visual attention has used the ‘gold standard’ measure of the  
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42 Psychomotor Vigilance Test (PVT), which has consistently been shown to be sensitive to  
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44 sleep deprivation (see Tkachenko & Dinges 2018, for a review). However, visual attention is  
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46 not limited to our ability to switch focus between stimuli; it is a complex system of  
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48 functionally and anatomically distinct brain networks, which support our ability to (i)  
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50 maintain an “alert” state (alerting network), (ii) “orient” attention to stimuli (orienting  
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52 network), and (iii) resolve conflict when numerous stimuli simultaneously compete for  
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54 attention (executive control network) (Fernandez-Duque & Posner, 2001; Petersen & Posner,  
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56 2012). These networks are governed by distinct neurobiological pathways (Fan & Posner,  
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58 2004) and they are individually supported by network-specific genetic modulators (Fossella  
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3 et al., 2002), making it likely that they are also differentially affected by sleep. Indeed,  
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5 previous research has registered differential effects of sleep deprivation on the functioning of  
6  
7 these distinct networks (see Tkachenko & Dinges, 2018). For example, one study compared  
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9 ANT performance at baseline vs. following 24-hours of sleep deprivation within subjects and  
10  
11 observed longer reaction times, poorer accuracy, and diminished P3 event-related potential  
12  
13 response following sleep deprivation (Trujillo, Kornguth, & Schnyer, 2009). Similarly,  
14  
15 another study demonstrated longer reaction times and impaired functioning of the orienting  
16  
17 and executive control networks following sleep deprivation compared to baseline (Martella,  
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19 Casagrande, & Lupianez, 2011); though these effects were only partially replicated by some  
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21 researchers (Jugovac & Cavallero, 2012) and not replicated by others (Muto et al., 2012;  
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23 Roca et al., 2012).

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29 Despite this growing body of research on the relationships between *experimentally*  
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31 induced sleep deprivation and the performance of attentional networks, a dearth of research  
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33 focuses on what happens in the real world. Our own previous work demonstrated that  
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35 impairments in attentional performance emerge after 18-hours of sustained wakefulness – a  
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37 period of wakefulness, which is typical of many adults during the working week (Barclay &  
38  
39 Myachykov, 2017). Given that today's society may foster inconsistent sleep patterns due to  
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41 the changing responsibilities on work- and free-days, it appears pertinent to examine in detail  
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43 the influence of sleep duration variability on attention, and to determine whether sleep  
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45 duration and its variability have differential effects on distinct attentional networks.  
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50 Thus, the present study investigated associations between sleep duration over one  
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52 week assessed by actigraphy and the efficiency of the attentional networks, as well as the  
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54 possibility that these associations are moderated by sleep duration variability. We  
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56 hypothesised that poorer attentional performance would be predicted by 1) shorter sleep  
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58 duration and greater sleep duration variability, independently; and 2) consistently  
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3 shorter/inconsistently longer sleep duration across the week. Given previously observed  
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5 chronotype and time-of-day effects on attentional performance (e.g. Barclay & Myachykov,  
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7 2017; Matchock & Mordkoff, 2009), analyses accounted for their potential direct and  
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9 interactive effects where relevant.  
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## 12 13 **Method**

### 14 15 16 *Participants*

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19 Participants were recruited from the general population of England through poster  
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21 advertisements, emails to staff and students of Northumbria University, Sheffield Hallam  
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23 University and University of Oxford, and through social media. To be eligible to participate,  
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25 potential participants had to be between 22-50 years of age; not taking any medications that  
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27 may affect their sleep; not have a history of/or current medical, neurological or psychiatric  
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29 illness (including anxiety or depression); not have a sleep disorder (treated or untreated); and  
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31 not be a shift worker. Fifty-eight participants meeting these eligibility criteria initially  
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33 enrolled in the study; 57 provided complete data (61.4% female; mean age = 32.37 years; SD  
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35 = 8.68; 61.4% female).  
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### 41 *Measures*

#### 42 43 44 *Screening questionnaire*

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47 An in-house screening questionnaire assessing sleep, sleep disorders, general health and  
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49 demographic information assessed eligibility for participation.  
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#### 52 53 *Sleep quality*

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56 Sleep quality over the past month was assessed using the Pittsburgh Sleep Quality Index  
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58 (PSQI: Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). The PSQI is an 18-item self-  
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3 report questionnaire, which assesses 7 components of sleep quality: subjective sleep quality,  
4 sleep latency, sleep duration, sleep efficiency, sleep disturbances, use of sleeping medication,  
5 and daytime dysfunction. Component scores are summed to produce a global sleep quality  
6 and daytime dysfunction. Component scores are summed to produce a global sleep quality  
7 score ranging from 0 to 21. Higher scores represent poorer sleep quality. Global sleep quality  
8 score was considered as a covariate in the statistical analyses if it was shown to be associated  
9 with the dependent variable of interest.  
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### 18 *Chronotype*

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21 Chronotype was assessed using the Morningness-Eveningness Questionnaire (MEQ: Horne  
22 & Östberg, 1976). The MEQ is a 19-item self-report questionnaire, which assesses preferred  
23 timing of daytime activities, sleep habits, hours of peak performance and times of ‘feeling  
24 best’ and maximum alertness. Responses are combined to provide a total score ranging from  
25 16 to 86. Higher scores represent a tendency towards morningness. Chronotype score was  
26 considered as a covariate in the statistical analyses if it was shown to be associated with the  
27 dependent variable of interest.  
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### 38 *Sleepiness*

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41 State sleepiness was assessed using the Stanford Sleepiness Scale (SSS: Hoddes, Zarcone, &  
42 Dement, 1972). The SSS is a 1-item measure assessing momentary alertness. Responses  
43 range from 1 (wide awake) to 7 (sleep onset soon). Sleepiness was considered as a covariate  
44 in the statistical analyses if it was shown to be associated with the dependent variable of  
45 interest.  
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### 54 *Actigraphy*

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57 Actilife GT3X and CamNtech Ltd. MW8 actiwatches were used to detect movement bouts,  
58 worn for seven consecutive nights on the non-dominant wrist. Data collection started  
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3 immediately following the initial laboratory visit and concluded on the morning of day 8.  
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5 Actilife 5 (Actigraph Corp, 2011) and Motionware 1.1.25 (CamNtech Ltd. 2009) software  
6  
7 was used to analyse the actigraphy data to provide summary statistics of the participants'  
8  
9 weekly sleep. We used the Sadeh Algorithm (Sadeh, Sharkey, & Carskadon, 1994) to  
10  
11 determine sleep/wake status for each 60 second (actilife) or 30 second (CamNtech) epoch  
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13 with 30Hz sample rate, as per device recommendations for optimal sleep recording (note that  
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15 there were no differences between device type on any of the independent variables or  
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17 outcomes of interest). Participants also kept daily sleep diaries, indicating bed-time and rise-  
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19 time and these times were entered into the software as start times for actigraphic analysis (i.e.  
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21 to indicate intention to sleep). Sleep duration was averaged for each participant across the  
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23 seven nights. Variability in sleep duration was calculated as the within-participant standard  
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25 deviation in sleep duration across the seven nights.  
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### 31 *Attention*

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35 The Attention Network Test (ANT: Fan, McCandliss, Sommer, Raz, & Posner, 2002) is a  
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37 computerised reaction time task used to examine the individual attentional networks'  
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39 performance (see Figure 1). In the ANT, participants perform on trials containing centre,  
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41 double, spatial cues, or no cues (100msec) between two central fixation events. At the second  
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43 central fixation (400msec), the target arrow (left or right) is presented either above or below  
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45 the fixation cross, and is either presented alone (neutral condition); with 2 flankers either side  
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47 pointing in the same direction (congruent condition); or with 2 flankers either side pointing in  
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49 the opposite direction (incongruent condition) (lasting no longer than 1700msec). Upon  
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51 presentation of the target, participants are required to indicate by pressing designated keys on  
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53 a computer keyboard whether the corresponding arrows point leftwards or rightwards. As  
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55 outlined by us previously (Barclay & Myachykov, 2017), the ANT provides a raw reaction  
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3 time (RT) measure for each of the conditions (cue type: no cue, centre cue, double cue,  
4 spatial cue; flanker type: neutral, congruent, incongruent) as well as error rates. Additionally,  
5  
6 the ANT provides specific measures of alerting, orienting and conflict resolution (executive  
7 control). The alerting score is calculated by subtracting the mean RT of the double-cue  
8 conditions (which alerts the participant to the imminent target, but provides no information  
9 on its location either above or below the cross) from the mean RT of the no-cue conditions.  
10  
11 The orienting score is calculated by subtracting the mean RT of the spatial cue conditions  
12 (which alerts participants to the imminent target and provides information on its location)  
13 from the mean RT of the centre cue conditions (which only alerts participants to the  
14 imminent target at one location). The conflict (executive control) score is calculated by  
15 subtracting the mean RT of all congruent flanked conditions from all incongruent flanked  
16 conditions (from all cue types). Lower scores typically indicate difficulty: a) maintaining  
17 alertness without a cue (alerting); b) disengaging from the centre cue (orienting); or c)  
18 resolving conflict (executive control) (Fan & Posner, 2004).  
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36 [{\(Insert Figure 1 here\)}](#)  
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### 39 ***Procedure***

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42 Interested participants completed the screening questionnaire to confirm eligibility. Eligible  
43 participants met with the researcher to provide their informed consent, and to receive an  
44 actiwatch and sleep diary as well as information regarding their use each day/night.  
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46 Participants wore actiwatches for seven consecutive nights, and they were informed that the  
47 week should be 'typical' for them. Participants returned to the laboratory on day 8 to hand  
48 back the actiwatch and sleep diary; to complete the PSQI, MEQ and SSS; and to participate  
49 in the ANT. Note that all participants completed the ANT between 8:00am and 8:00pm (57%  
50 completed the ANT before 12:00pm and 89% before 6:00pm). Time of testing was included  
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3 in statistical analyses as a covariate. All procedures complied with the ethical principles laid  
4 out by the American Psychological Association and the Declaration of Helsinki. Approval  
5 was granted by Oxford Central University Research Ethics Committee and Northumbria  
6 University Psychology Department Ethics Committee.  
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### 16 *Statistical Analyses*

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19 Previous researchers observed a large effect size for change in  $R^2$  for sleep duration  
20 variability predicting one facet of attention (Whiting & Murdock, 2016). In the present study,  
21 a power calculation using G\*Power indicated that to identify large effects as hypothesised  
22 (i.e.  $F^2$  for  $\Delta R^2 \geq .35$ ), 47 participants would be required to achieve 90% power with an  $\alpha < .01$   
23 (Cohen, 1988). Our final sample of 57 participants provided sufficient power to address our  
24 hypotheses. Descriptive statistics were first derived followed by t-tests to examine possible  
25 sex differences in the dependent and independent variables. Correlations between dependent  
26 variables, independent variables and potential covariates were then examined. A repeated-  
27 measures within-subjects ANOVA was performed to examine the sensitivity of the ANT in  
28 the current sample. A series of hierarchical regression models were then run for each  
29 dependent variable (overall mean reaction time  $\{RT\}$ , alerting, orienting and executive  
30 control scores, and overall error rates). Covariates that were significantly correlated with the  
31 outcome variables were incorporated in regression models in the first steps (age, chronotype  
32 and time of testing). In each regression model, predictor variables and covariates were grand  
33 mean centred. A reciprocal transformation was applied to the error rate data to reduce  
34 positive skew. Simultaneous regression models were also run to derive individual coefficients  
35 for each predictor/covariate for significant models.  
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3 We examined five models in separate blocks as follows: 1) covariate 1 (if applicable); 2)  
4 covariate 2 (if applicable); 3) sleep duration; 4) sleep duration variability; and 5) sleep  
5 duration X sleep duration variability interaction. Moderation models were run using the  
6 PROCESS tool for SPSS (Hayes, 2013) in order to further examine significant interactions.  
7  
8 Of note, linear regression models were also run with covariates entered in the last steps in  
9 order to examine potential mediation effects. Mediation effects were not indicated for any  
10 models (models not reported, available upon request). Significance of each model, and each  
11 predictor within each model, was considered at a Bonferroni corrected level of  $p < .01$  (.05/5)  
12 to account for the multiple testing of ANT-derived dependent variables.  
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## 24 **Results**

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27 Mean sleep quality score was 4.39 (SD=2.24) indicating good sleep, and chronotype score  
28 was 54.47 (SD=10.43) indicating a largely ‘neither’ type chronotype. Mean actigraphically  
29 measured sleep duration across the week was 421.45 mins (SD=39.70; range 336.71 mins to  
30 541.71 mins), and mean variability in sleep duration across the week was 60.99 mins  
31 (SD=38.42; range 16.22 mins to 256.14 mins). Mean ANT reaction times were pooled from  
32 all correct trials for all participants. Incorrect trials accounted for 3.65% of the total trials.  
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34 Additionally, trials with RT <200ms and >4 absolute deviations from the median (MAD, see  
35 Leys, Ley, Klein, Bernard & Licata, 2013, for information) were excluded from analysis  
36 (2.87% of correct trials). In total, 6.41% of trials were excluded. Table 1 shows the mean RT  
37 and SD, and Table 2 the mean error rates and SD, for each of the experimental conditions (4  
38 x cue type; 3 x flanker type).  
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54 [{\(Insert Tables 1 and 2 here\)}](#)

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57 There were sex differences in actigraphically derived mean sleep durations ( $t(55) =$   
58  $-2.89$ ,  $p < .05$ , [Hedges’  \$g = .79\$](#) ). Males had significantly shorter mean sleep duration  
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(mean=403.44 mins; SD=34.39) than females (mean=432.76 mins, SD=39.03). There were also significant sex differences in orienting, ( $t(55) = -2.35$ ,  $p < .05$ , Hedges'  $g = .64$ ). Orienting score for males was significantly lower (mean=22.11; SD=17.63) than females (mean=33.94; SD=19.00) suggesting that females were faster to orient their attention. There were no sex differences in any of the remaining key actigraphically assessed sleep variables or key ANT variables (sleep duration variability:  $t(55) = .95$ ,  $p = .35$ ; overall RT:  $t(55) = -.54$ ,  $p = .59$ ; alerting:  $t(55) = .55$ ,  $p = .59$ ; executive control:  $t(55) = .16$ ,  $p = .87$ ; and overall error rates:  $t(55) = .04$ ,  $p = .97$ ). There were several significant correlations that are fundamental to the analyses (see Table 3): 1) older age and longer overall RTs; 2) lower sleep duration variability and poorer alerting scores; 3) older age and poorer alerting scores; 4) earlier time of testing and poorer alerting scores; 5) younger age and poorer orienting scores; and 6) increasing tendency towards eveningness and poorer orienting scores.

{(Insert Table 3 here)}

A repeated-measures ANOVA was performed on mean overall RTs, with cue (no cue, centre, double and spatial cues) and flanker type (neutral, congruent and incongruent) as within-subject factors. Assumptions of sphericity were not met for the main effects of cue and flanker type, and the interaction between cue and flanker type. Consequently, Greenhouse-Geisser correction to degrees of freedom was employed. There were significant main effects of cue, ( $F(2.50, 137.52) = 176.27$ ,  $p < .01$ ,  $\eta_p^2 = .76$ ) and flanker type, ( $F(1.45, 79.82) = 1040.91$ ,  $p < .01$ ,  $\eta_p^2 = .95$ ) on mean overall RT, and a significant interaction between cue and flanker type, ( $F(4.37, 240.51) = 12.92$ ,  $p < .05$ ,  $\eta_p^2 = .19$ ). Longer reaction times were registered in trials with no cue vs. all other cues (relevant to alerting and orienting); and incongruent vs. both other flanker types (relevant to executive control).

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3 A series of hierarchical linear regression models were run separately for each outcome  
4 variable (see Tables 4-6). For mean overall RT as the dependent variable, model 1 (including  
5 age) was significant, ( $F(1,56)=9.03, p=.00$ ), and model 4 (including age, sleep duration,  
6 sleep duration variability and the sleep duration X sleep duration variability interaction)  
7 significantly improved model fit, ( $\Delta F(1,52)=4.52, p=.04$ ). The final model explained 22%  
8 of variance in overall RT (see Table 4). From the simultaneous regression model, age was a  
9 significant predictor of overall RT, such that older age predicted longer overall RTs ( $\beta=.35,$   
10  $t=2.70, p=.01$ ), as was the sleep duration X sleep duration variability interaction ( $\beta=-.34, t=-$   
11  $2.13, p=.04$ ). Moderation analysis in PROCESS revealed that the slowest RTs were  
12 predicted by shorter sleep duration and high sleep duration variability, and that the fastest  
13 RTs were predicted by longer sleep duration and high sleep duration variability ([t values for](#)  
14 [each moderator level: low:  \$t=.36, p=.72\$ ; medium:  \$t=-1.11, p=.27\$ ; high:  \$t=-2.21, p=.03\$](#) ) (see  
15 Figure 2a).

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34 [{\(Insert Table 4 here\)}](#)  
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37 For alerting score as the dependent variable, Models 2 (including age and time of  
38 testing) and 5 (including age, time of testing, sleep duration, sleep duration variability and the  
39 sleep duration X sleep duration variability interaction) significantly improved model fit,  
40 ( $\Delta F=10.32, p=.00$ ; and  $\Delta F=8.62, p=.01$ , respectively). The final model explained 37%  
41 of variance in alerting score. From the simultaneous regression model, time of testing and the  
42 sleep duration X sleep duration variability interaction significantly predicted alerting score  
43 ( $\beta=-.22, t=-2.96, p=.01$ ; and  $\beta=.43, t=2.94, p=.01$ ). Moderation analysis in PROCESS  
44 revealed that the poorest alerting score was predicted by longer sleep duration and low sleep  
45 duration variability, and that the best alerting score was predicted by longer sleep duration  
46 and high sleep duration variability ([t values for each moderator level: low:  \$t=-1.15, p=.25\$ ;](#)  
47 [medium:  \$t=.53, p=.60\$ ; high:  \$t=2.17, p=.03\$](#) ) ( $t=2.54, p=.01$ ) (see Figure 2b). Because of the  
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3 strength of the correlation between sleep duration variability and alerting score (Table 3), we  
4 decided to examine the extent to which sleep duration moderates this association. We  
5 performed a median split on the sleep duration variable and performed moderation analysis in  
6 PROCESS. It appeared that long sleep duration drives the association between sleep duration  
7 variability and alerting score (t value for short and long sleep duration: short:  $t=-.57=2.03$ ,  
8  $p=.57$ ; long:  $t=3.26$ ,  $p=.0004$ ) (see Figure 2c).

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18 {(Insert Table 5 and Figures 2a, 2b and 2c here)}  
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21 Due to the unexpected direction of the interaction effect (i.e. that long sleep duration  
22 with low sleep duration variability predicted poorest alerting), we further visualised the  
23 distribution of sleep duration variability and alerting score (see Figure 3a). The presence of  
24 an outlier experiencing high sleep duration variability and high alerting score is present in the  
25 data (256.14 mins and alerting score of 110.8). Indeed, inspection of the nightly sleep  
26 duration data for this individual revealed nightly sleep durations ranging from 142 mins to  
27 924 mins, the latter of which occurred the night prior to testing. Inspection of the distribution  
28 of sleep duration the night prior to testing and alerting score also revealed the contribution of  
29 this outlier to the association (Figure 3b). The average sleep duration experienced by this  
30 participant was not unusual (501.43 mins); hence the distribution of mean sleep duration and  
31 alerting appears normal (Figure 3c). Due to the presence of this outlier, we re-ran the  
32 correlations after excluding this participant. The association between sleep duration  
33 variability and alerting reduced from .34 ( $p<.01$ ) to -.03 ( $p=.82$ ); and the association between  
34 sleep duration the night prior to testing and alerting reduced from .30 ( $p<.05$ ) to -.06 ( $p=.65$ ).  
35 The regression analyses were re-run after exclusion of this participant, and the pattern of  
36 results for overall RT as the dependent variable changed such that the interaction term was no  
37 longer significant (though age remained a significant predictor of overall RT ( $\beta=.36$ ,  
38  $t=2.65$ ,  $p=.01$ ); likewise for alerting as the dependent variable the interaction between sleep  
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3 duration X sleep duration variability reduced to non-significance, whilst time of testing  
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5 remained a significant predictor ( $\beta=.37, t=2.85, p=.01$ ).  
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9 For orienting score as the dependent variable, model 1 (including age) and model 2  
10 (including age and chronotype) significantly improved model fit ( $\Delta F=4.73, p=.03$ ; and  
11  $\Delta F=5.54, p=.02$ , respectively). Model 2 explained 16% of variability in orienting score.  
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13 From the simultaneous regression model, only chronotype significantly predicted orienting  
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15 score ( $\beta=.31, t=2.28, p=.03$ ) such that a tendency towards morningness was associated with  
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17 better orienting. These results remained after excluding the anomalous participant.  
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24 [{\(Insert Table 6 here\)}](#)  
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27 For executive control scores and overall error rates, all regression analyses were non-  
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29 significant (all model  $p$ 's  $>.05$ ) (both with the inclusion and exclusion of the anomalous  
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31 participant).  
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35 [{\(Insert Figure 3 here\)}](#)  
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## 37 **Discussion**

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41 The results presented here expand previous research investigating the importance of  
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43 sleep for optimum cognitive functioning. Here we extend research from experimental sleep  
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45 deprivation studies, to demonstrate the influence of normal sleep duration variability in the  
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47 general population on various components of visual attention. There are four key findings  
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49 stemming from this study: 1) neither sleep duration, nor sleep duration variability, nor their  
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51 interaction, were predictive of orienting, executive control or error rates; 2) earlier time of  
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53 testing was associated with poorer efficiency of the alerting network; 3) the associations  
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55 between sleep duration with overall reaction time and efficiency of the alerting network  
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57 *appeared* to be moderated by sleep duration variability; however, the presence of an outlier  
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3 experiencing high sleep duration variability and extremely long sleep duration the night prior  
4 to testing appeared to solely account for the interactive effects of sleep duration and sleep  
5 duration variability on overall reaction time/ alerting score; and 4) older age was associated  
6 with longer overall reaction times, and this was independent of sleep duration and sleep  
7 duration variability. Below we explain these findings in relation to our initial hypotheses and  
8 in the context of the emerging field.  
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25 ***Sleep duration and sleep duration variability did not predict orienting score, executive***  
26 ***control score or error rates***  
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30 Contrary to our hypotheses, we did not find that sleep duration or sleep duration  
31 variability predicted components of attention (the efficiency of the orienting network, the  
32 efficiency of the executive control network, or proportion of errors made). Likewise, the  
33 interaction between sleep duration and sleep duration variability was not a significant  
34 predictor of these measures of attention. Other experimental studies show a general detriment  
35 to sustained attention under varying degrees of sleep deprivation, fragmentation and  
36 restriction (see Tkachenko & Dinges, 2018 for a review) while observational studies similarly  
37 show that consistently short sleep duration is associated with attentional disengagement  
38 (Whiting & Murdock, 2016). Our data does not show a similar effect, at least in terms of  
39 orienting, executive control and accuracy.  
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54 There are a couple of plausible explanations for this. First, it is possible that these  
55 particular ANT-derived variables are insensitive to natural variation in sleep duration and  
56 intra-individual sleep duration variability. The experimental sleep-deprivation literature  
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3 indeed suggests that whilst sustained attention (which would be analogous to our measure of  
4 overall reaction time) and alerting are particularly sensitive to sleep loss, other attentional  
5 functions, including orienting and executive function, may remain spared (Cunningham,  
6 Jones Eskes & Rusak, 2018; Roca et al., 2012; Tkachenko & Dinges, 2018, but see Martella,  
7 Casagrande, & Lupianez, 2011). Second, it is possible that there was not enough variability in  
8 our data for such effects to emerge. Indeed, we sampled the average sleep duration over the  
9 course of 7 days in healthy good sleepers, and asked them to maintain their ‘habitual’ sleep  
10 patterns. The standard deviation of our ‘mean sleep duration’ variable was 39.90 minutes, and  
11 86% of our sample had a mean sleep duration between 6-8 hours. Thus, it is possible that  
12 meaningful effects on attentional performance occur at far greater extremes of sleep duration  
13 than the ones exhibited by our sample. Studies examining consequences of sleep duration  
14 variation often focus on greater extremes, and demonstrate a U-shaped curve: highlighting  
15 the detrimental effects of both short (conceptualised as <6 hours per night) and long (usually  
16 conceptualised as >8 hours per night) sleep duration on various indicators of health (Patel &  
17 Hu, 2008), all-cause mortality (Cappuccio et al., 2010), and cognition (Kronholm et al.,  
18 2009). Our intention was to show that in the ‘real-world’ consistently short sleep or  
19 inconsistently long sleep results in deficits in attention, yet it is possible that our selection  
20 process yielded a sample of healthy good sleepers that failed to allow these patterns to  
21 emerge. Future research needs to encapsulate more variable sleep-wake patterns to truly  
22 describe the heterogeneity of sleep (by including those with sleep disturbances/more variable  
23 sleep-wake patterns such as shift workers) that exists in the general population and examine  
24 concomitant associations with cognition.  
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54 Third, effects of sleep duration and sleep duration variability may have been obscured  
55 by the effect of time of testing. Whilst the majority of our participants completed the ANT  
56 before midday, we did not strictly control time of testing, and so testing was performed up  
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3 until 8pm. Had time of testing been consistent, we may have seen an effect of sleep duration  
4 emerge. Matchock and Mordkoff (2014) for example, observed increased reaction times on  
5 the ANT *upon awakening* under conditions of restricted sleep durations of 3-hours and 6-  
6 hours, compared to a baseline condition of normal sleep duration. However, the results of  
7 Matchock & Mordkoff may actually reflect “sleep inertia” or result from testing at  
8 suboptimal circadian phase in the early morning, rather than purely the effect of short sleep  
9 duration. We chose not to restrict our testing time to *upon awakening* as we wanted to rule  
10 out the effect of sleep inertia, and we wanted to examine potential effects of time of testing.  
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23         Nevertheless, our data revealed a reliable effect of time of testing on the efficiency of  
24 the alerting network. The alerting network efficiency was progressively better as the time of  
25 testing was later in the day. This finding is partially consistent with the studies that observed  
26 significant time-of-day effects on the alerting, orienting and executive control networks  
27 (Matchock & Mordkoff, 2009; Fimm, Brand & Spijkers, 2016), and corroborates what is  
28 typically observed in relation to the circadian rhythm of neurobehavioural functioning: it is  
29 poor upon awakening in the morning, and then steadily improves across the waking day to a  
30 peak around early evening, followed by a progressive decline into the night (Goel et al.,  
31 2011; Mollicone et al., 2010). Taken together, these findings highlight the importance of  
32 systematically isolating variables relating to the sleep homeostat and the circadian rhythm.  
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***Associations between sleep duration with overall reaction time and efficiency of the alerting network appeared to be moderated by sleep duration variability***

Contrary to our hypotheses, shorter sleep duration coupled with high sleep duration variability predicted the longest overall reaction times, and longer sleep duration coupled

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3 with high sleep duration variability predicted the shortest reaction times. Concerning alerting,  
4 longer sleep duration coupled with low sleep duration variability appeared to be associated  
5 with poorer efficiency of the alerting network, whilst on the other hand longer sleep duration  
6 coupled with high sleep duration variability appeared to be associated with better efficiency  
7 of the alerting network. However, further inspection of our data revealed that these effects  
8 were accounted for by an individual exhibiting extremely high sleep duration variability, and  
9 extremely long sleep duration the night prior to testing – with this participant excluded, these  
10 interaction effects were reduced to non-significance. This finding highlights the importance  
11 of considering the nightly variability in sleep duration when taking an average of such data.  
12 Many research studies rely on taking an average of sleep variables across a pre-specified time  
13 period (3 nights, a week), but such crude measures fail to capture the nightly variability in  
14 sleep duration. With this participant excluded, the standard deviation of our sleep duration  
15 variability predictor reduced from 38.41 to 28.24. Thus, our data were perhaps too  
16 homogenous for important effects on reaction time and alerting to emerge.  
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#### 36 *Association between Age And Overall Reaction Time:*

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38 Perhaps less surprising in our study was the finding that older age was associated with  
39 longer overall reaction time. It appears that the relative deficit in attention shown here stems  
40 from age-related factors rather than short sleep duration per se. The efficiency of the alerting  
41 network is significantly impaired in older adults comparative to younger adults (Gamboz,  
42 Zamarian, & Cavallero, 2010; Jennings, Dagenbach, Engle, & Funke, 2007). Given that sleep  
43 patterns dramatically change across the lifespan (Ohayon, Carskadon, Guilleminault, &  
44 Vitiello, 2004), it is pertinent to further investigate the interactive effects of aging and sleep  
45 on cognition. Others have hypothesised that increased reaction time following sleep  
46 restriction results from diminished oculomotor functioning (Zils, Sprenger, Heide, Born, &  
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3 Gais, 2005), and this effect may become more pronounced as we age, given the natural  
4 progression of oculomotor functioning across the lifespan (Katsanis, Iacono, & Harris, 1998).  
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### 8 ***Limitations and Conclusions:***

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10 It is worth noting a couple of key limitations of the present study: 1) Our analyses focus on  
11 sleep duration and sleep duration variability rather than other indices of sleep, such as sleep  
12 onset latency, sleep efficiency, wake after sleep onset and number of awakenings. However,  
13 our sample size did not allow us to assess these variables at an acceptable level of power.  
14 Additionally, we wanted to focus on a variable that is to some extent under voluntary control,  
15 i.e., we can control the time we go to bed and the time we get out of bed, and by consequence  
16 our sleep duration, whereas we cannot control our sleep onset latency. We wanted to address  
17 a variable that can be behaviourally manipulated, and thus be the potential target of  
18 interventions to improve sleep and, by consequence, cognition. Further investigation of sleep  
19 under normal conditions (rather than the artificial setting of experimental sleep restriction/  
20 deprivation), investigating an array of sleep characteristics in a more heterogeneous sample  
21 will further shed light on the role of sleep duration and its variability on attention. 2) Our  
22 objective measure of sleep using actigraphy is not completely free of subjective biases, as the  
23 calculation of sleep parameters is partially dependent on subjectively reported bed times and  
24 rise times. Measuring sleep by using polysomnography would not only address this issue, but  
25 would also provide us with the opportunity to examine architectural properties of sleep  
26 macro- and micro-structure to identify the residual neural underpinnings of attention.  
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50 To conclude, this work did not demonstrate an effect of actigraphically measured  
51 sleep duration or sleep duration variability on measures of visual attention. However, this  
52 conclusion is derived from data focussing on the healthy population, experiencing good sleep.  
53 We do not rule out the possibility that poor sleep and inconsistencies in sleep patterns  
54 contribute to cognitive impairments in populations for whom sleep is disturbed.  
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## Table Captions

Table 1. Mean and SD RT (msec) for each experimental condition of the ANT (correct trials only and *4 absolute deviations from the median* excluded)

Table 2. Percentage of errors (SD) for each experimental condition of the ANT

Table 3. Correlations between key dependent variables, independent variables and potential covariates

Table 4. Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting overall reaction time

Table 5. Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting alerting

Table 6. Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting orienting

## Figure Captions

Figure 1. Attention Network Test procedure. (a) The four cue conditions; (b) The flanker types; and (c) An example of the procedure. Reprinted from Fan et al (2002) with permission granted by Prof. Posner.

Figure 2. Moderation models in PROCESS of a) association between sleep duration and overall reaction times moderated by sleep duration variability; b) association between sleep duration and alerting score moderated by sleep duration variability. Separate lines represent low (22.58 mins), medium (61 mins) and high (99.41 mins) sleep duration variability; and c) association between sleep duration variability and alerting score moderated by sleep duration



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3 derived by median split (short sleepers  $<419.14$  minutes; long sleepers  $\geq 419.14$  minutes).

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5 Higher alerting scores indicate better efficiency of the alerting network.  
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9 Figure 3. Scatterplots of a) the association between sleep duration variability and alerting  
10 score, showing the presence of an outlier experiencing high sleep duration variability; b) the  
11 association between sleep duration the night before testing and alerting score, showing the  
12 presence of an outlier experiencing long sleep duration the night before testing; and c) the  
13 association between mean sleep duration and alerting score. Higher alerting scores indicate  
14 better efficiency of the alerting network.  
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Table 1

*Mean and SD RT (msec) for each experimental condition of the ANT (correct trials only and outliers 4 absolute deviations from the median excluded)*

Flanker Types	Cue			
	No cue	Centre	Double	Spatial
Neutral	557.46 (47.40)	514.37 (52.41)	515.71 (56.85)	492.07 (51.01)
Congruent	609.17 (57.44)	572.16 (58.00)	569.46 (69.30)	547.95 (55.85)
Incongruent	716.57 (60.14)	710.17 (62.59)	703.26 (67.64)	664.84 (63.83)

Note. ANT = Attention Network Test; msec = milliseconds; SD = standard deviation

Table 2

*Percentage of errors (SD) for each experimental condition of the ANT*

Flanker Types	Cue			
	No cue	Centre	Double	Spatial
Neutral	3.93% (19.44%)	3.53% (18.46%)	3.38% (18.08%)	2.53% (15.72%)
Congruent	1.43% (11.88%)	0.85% (9.21%)	1.24% (11.09%)	1.81% (13.35%)
Incongruent	7.11% (25.71%)	8.02% (27.17%)	8.13% (27.34%)	6.75% (25.10%)

Note. ANT = Attention Network Test; SD = standard deviation



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 Predictor Variables
 

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6. Mean Sleep    -.20    .16    -.07    .00    .00    /

Duration

7. Sleep        -.14    .34\*\*    -.10    .10    .18    .17    /

Duration

Variability

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 8. Sleep        -.19    .30\*    -.10    .07    .18    .66\*\*    .47\*\*    /

Duration

Night

before

testing

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 Potential Covariates
 

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9. Age            .38\*\*    -.26\*    .28\*    .18    -.03    -.28\*    -.20    -.21    /

10. Time ANT	-.25	.40**	.19	.16	-.10	.16	.27*	.16	-.02	/			
tested													
11. Sleepiness	-.19	.19	.08	.05	-.03	.11	-.03	.11	-.12	.13	/		
12. Sleep Quality	-.10	.14	.12	.13	-.07	-.13	-.07	-.04	.15	.23	.35**	/	
13. Chronotype	.23	-.04	.36**	.23	-.11	-.13	-.19	-.20	.28*	.11	-.03	.29*	/

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Note. \*  $p < .05$ ; \*\*  $p < .01$  (Bonferroni corrected). ANT = Attention Network Test. All variables are raw scores.

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Table 4

*Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting overall reaction time*

Covariates/ Predictors	<u>Hierarchical Regression</u>				<u>Regression Coefficients of Predictors/Covariates (Simultaneous Entry)</u>					
	$\Delta R^2$	$R^2$	Adj $R^2$	$p \Delta F$	$B$	SE $B$	$\beta$	$T$	$p$	
Age	.14	.14	.13	.00	2.09	.77	.35	2.70	.01	
Sleep Duration	.01	.15	.12	.44	-.08	.17	-.06	-.45	.65	
Sleep Duration Variability	.00	.15	.11	.65	.20	.22	.15	.94	.35	
Sleep Duration X Sleep Duration Variability	.07	.22	.16	.04	-.01	.00	-.34	-2.13	.04	

Note. Analyses were performed with centred predictors and covariates.

Table 5

*Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting alerting*

Covariates/ Predictors	<u>Hierarchical Regression</u>				<u>Regression Coefficients of Predictors/Covariates (Simultaneous Entry)</u>				
	$\Delta R^2$	$R^2$	Adj $R^2$	$p \Delta F$	$B$	SE $B$	$\beta$	$T$	$p$
Age	.07	.07	.05	.05	-.53	.28	-.22	-1.87	.07
Time of Testing	.15	.22	.19	.00	2.06	.70	.35	2.96	.01
Sleep Duration	.00	.22	.18	.82	-.02	.06	-.03	-.28	.78
Sleep Duration	.04	.26	.20	.13	-.04	.08	-.07	-.47	.64
Variability									
Sleep Duration X Sleep	.11	.37	.30	.01	.00	.00	.43	2.94	.01
Duration Variability									

Note. Analyses were performed with centred predictors and covariates.



Table 6

*Multiple regression analyses of mean sleep duration, sleep duration variability and covariates predicting orienting*

Covariates/ Predictors	<u>Hierarchical Regression</u>				<u>Regression Coefficients of</u>				
	<u>Indices</u>				<u>Predictors/Covariates (Simultaneous</u>				
					<u>Entry)</u>				
	$\Delta R^2$	$R^2$	Adj $R^2$	$p$	$B$	SE $B$	$\beta$	$T$	$p$
Age	.08	.08	.06	.03	.46	.31	.21	1.50	.14
Chronotype	.08	.16	.13	.02	.56	.25	.31	2.28	.03
Sleep Duration	.00	.16	.12	.81	.02	.07	.05	.33	.74
Sleep Duration Variability	.00	.16	.10	.93	.03	.08	.06	.34	.74
Sleep Duration X Sleep Duration Variability	.01	.17	.10	.51	-.00	.00	-.11	-.66	.51

Note. Analyses were performed with centred predictors and covariates.

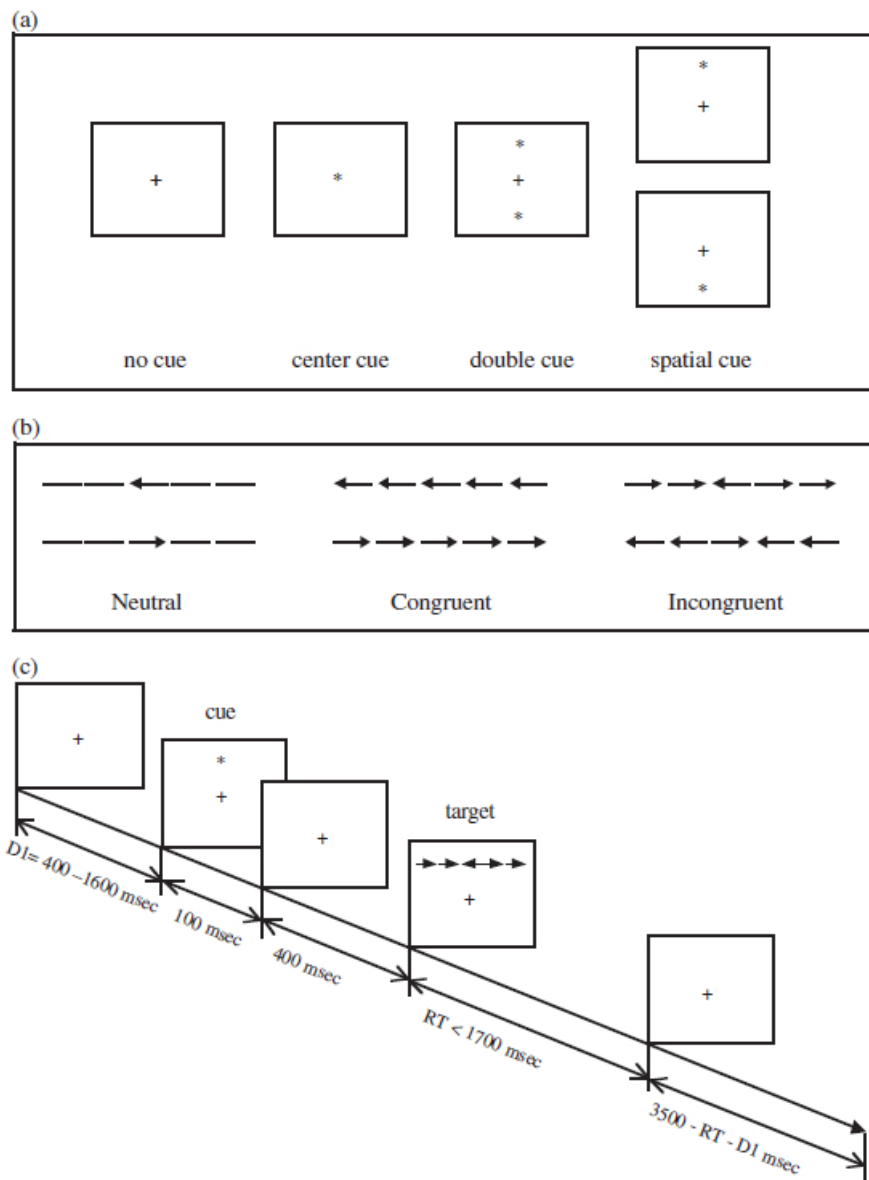


Figure 1. Attention Network Test procedure. (a) The four cue conditions; (b) The flanker types; and (c) An example of the procedure. Reprinted from Fan et al (2002) with permission granted by Prof. Posner.

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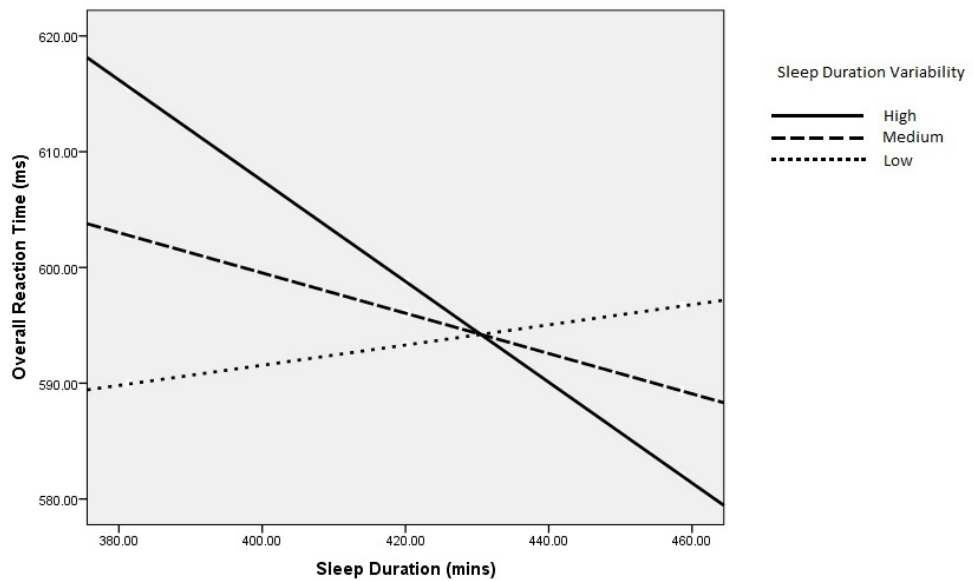


Figure 2a. Moderation model in PROCESS of association between sleep duration and overall reaction times moderated by sleep duration variability

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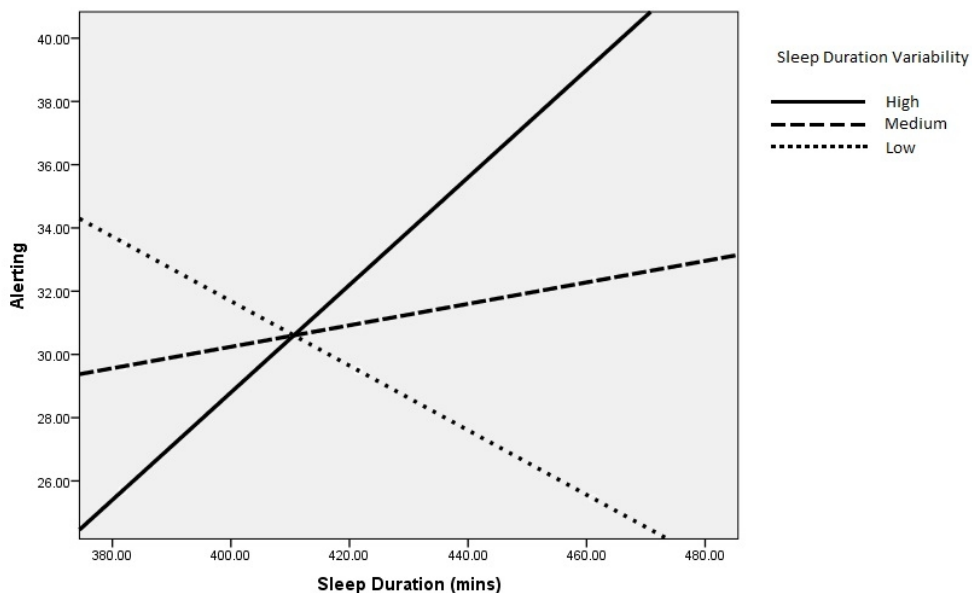


Figure 2b. Moderation model in PROCESS of association between sleep duration and alerting score moderated by sleep duration variability. Separate lines represent low (22.58 mins), medium (61 mins) and high (99.41 mins) sleep duration variability. Higher alerting scores indicate better efficiency of the alerting network.

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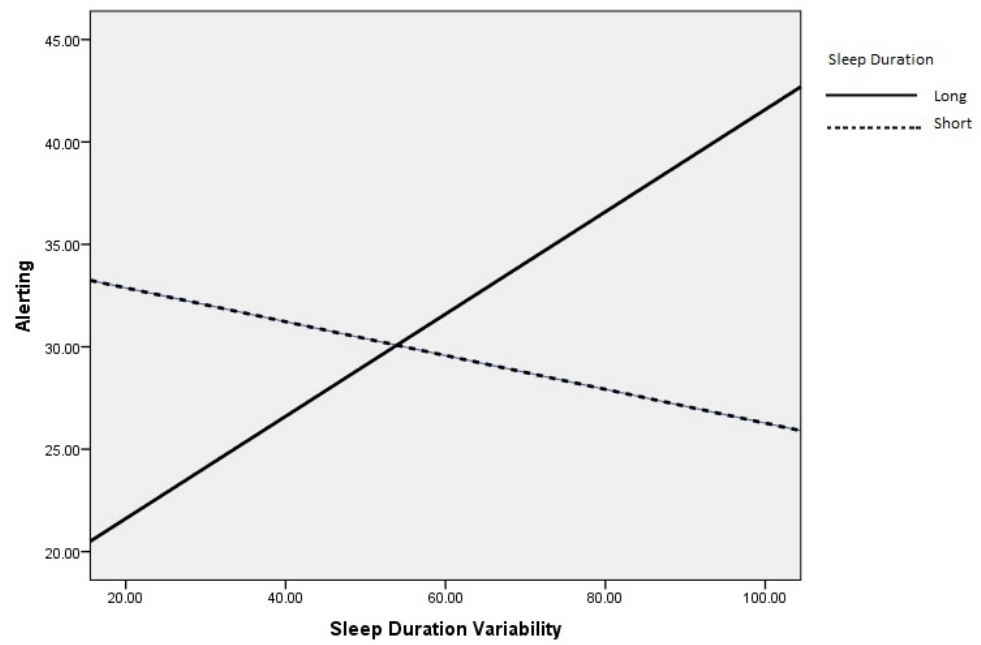


Figure 2c. Moderation model in PROCESS of association between sleep duration variability and alerting score moderated by sleep duration derived by median split (short sleepers <419.14 minutes; long sleepers  $\geq$ 419.14 minutes). Higher alerting scores indicate better efficiency of the alerting network.

202x133mm (96 x 96 DPI)

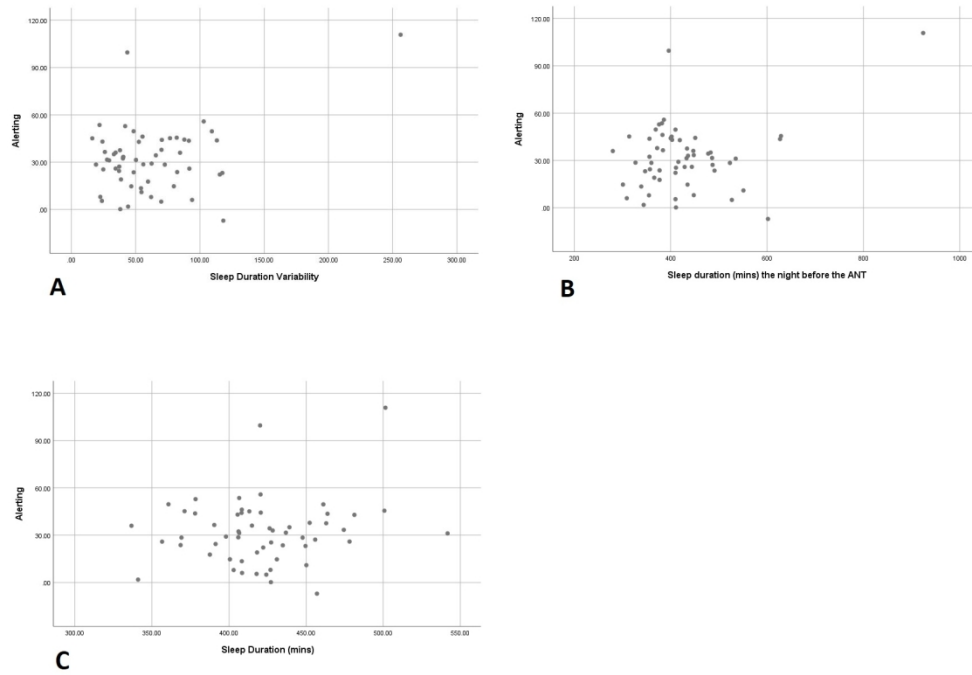


Figure 3. Scatterplots of a) the association between sleep duration variability and alerting score, showing the presence of an outlier experiencing high sleep duration variability; b) the association between sleep duration the night before testing and alerting score, showing the presence of an outlier experiencing long sleep duration the night before testing; and c) the association between mean sleep duration and alerting score. Higher alerting scores indicate better efficiency of the alerting network.

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