The Effects of Sleep Deprivation on Attentional Vigilance and Resting-state Electroencephalography

By
Ashley Jollie

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Approved: Dr. Jason Ivanoff
Supervisor

Approved: Dr. Benjamin Rusak
Committee Members

Approved: Dr. Steven Carroll
Committee Members

Approved: Dr. Derek Fisher
External Examiner

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Abstract: Sleep deprivation has been associated with poor vigilance performance. Previous studies have demonstrated performance decrements on the psychomotor vigilance task (PVT) and changes to resting-state EEG (rEEG) power. This study was designed to link diminished vigilance with rEEG after sleep deprivation to identify underlying mechanisms. In this study, rEEG and the 10-minute PVT were used after a full night's sleep or sleep deprivation. Absolute alpha power decreased when eyes were closed for the sleep deprivation condition, but not for the sleep condition. Furthermore, the response times on the PVT increased following sleep deprivation, but not after a normal night of sleep. Interestingly, no correlation was observed between the PVT and changes to rEEG spectral power. These findings suggest that the impairment in vigilance following sleep deprivation may not be directly tied to changes in rEEG spectral power. The findings are discussed within the context of contemporary theories of sleep deprivation.

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Insufficient sleep can have negative effects on performance resulting in catastrophes. For example in January 1986, the space shuttle “Challenger” exploded over the Atlantic Ocean. The disaster was attributed to human error. A final report of the incident indicated that NASA managers were severely sleep deprived at the time, jeopardizing job performance (Lineberry, 2009). Unfortunately this was not the only disaster that has occurred due to sleep loss. Investigations on the “Three Mile Island disaster” and the nuclear meltdown at Chernobyl ruled that sleep deprivation, resulting in inattention, was a leading factor in these disasters ("Sleep, Performance, and Public Safety," 2007). Thus, it is important to understand the underlying neural and behavioural effects of sleep deprivation due to the serious consequences of sleep loss.

Sleep

Sleep stages. There are two main groups of sleep stages, rapid eye movement (REM) and non-rapid eye movement (NREM). REM sleep occurs when rapid saccadic eye movement, postural atonia, and desynchronized EEG activity occur (Hori et al., 2001; Kolb & Whishaw, 2004; Wilchlinski, 1990). During REM sleep, twitching (eyes, toes and mouth movements) can occur and lasts no longer than 0.5 seconds (Hori et al., 2001). Non-REM sleep precedes REM. During non-REM, sleep onset occurs and slow eye movements are observed (Hori et al., 2001; Kolb & Whishaw, 2004).

To quantify and categorize stages between wakefulness and sleep, researchers use polysomnography that includes the following measures: electrooculography (EOG), electromyography (EMG), and electroencephalography (EEG). The EOG reflects the position and movements of the eyes while the EMG reflects the activity of muscles at the electrode site (typically placed on the chin). EEG refers to the electrical potential between the surface of the scalp and a scalp electrode that is referenced to a particular electrode or a pooled group of electrodes for a reference montage. EEG reflects the continuous and repetitive electrical activity resulting from the synchronous activity of neurons beneath the scalp (Fingelkurts and Fingelkurts, 2010; Klimesch, 1999; Miller, 2007; Schnakers, Majerus, & Laureys, 2005). EEG activity is wave-like and comprised of a number of different frequencies, ranging from 1 Hz to 100 Hz. There are four EEG rhythmic frequency bands that are of general research interest: alpha (8-12 Hz), beta (13-35 Hz), delta (1-4 Hz), and theta (4-8 Hz) (Miller, 2007).

During an awake/alert state, beta frequencies are dominant (Lavie, 1993). When the eyes are closed alpha frequencies are observed in an awake/alert state. However, when the eyes are closed a decline in alpha is observed as a person falls asleep (Hori et al., 2001; Iber et al., 2007). Once a person is preparing for sleep (or in an awake but relaxed state) the dominance of beta frequencies is replaced with alpha frequency dominance (Lavie, 1993). After several minutes in a relaxed state, EEG alpha activity may transition to theta frequencies. In polysomnography, N1 of NREM sleep is characterized by frequencies ranging from 4 Hz-8 Hz (theta) and slow regular eye movements (Hori et al., 2001; Iber et al., 2007). Theta represents the “transition stage” of going from awake to full sleep. After N1 of sleep, sleep spindles with a frequency range from 11Hz-16Hz are seen, including K complexes that are not associated with arousal. This is classified as N2. K complexes are sharp, negative waves that last longer than 0.5s (Iber et al., 2007; Hori et al., 2001). During N3, frequency activity decreases to 1 Hz-4 Hz (delta activity) where eye movements are not usually observed (Iber et al., 2007). During REM sleep theta activity is seen with short bursts of alpha activity (Lavie, 1993) and short, irregular bursts of EMG activity can be seen (Hori et al., 2001; Iber et al., 2007). To understand sleep it is important to comprehend the sleep/wake interaction and how it occurs.

Homeostatic/circadian processes and the sleep/wake cycle. Sleep arises from two processes. The first is *homeostatic*, a physiological mechanism that maintains a steady state regulating sleep/wake states to an internal reference level (Borbély, 1982). The second is *circadian*, an internal clock responsible for the timing of sleep/wake cycles (Borbély, 1982). The convergence between homeostatic and circadian process determines the duration of sleep and wake states (Achermann, 2004; Borbély, 1982; Dijk & Lockley, 2002; Putilov, 2011). When a person changes their normal sleep/wake cycle by missing a night of sleep, the circadian process is still attempting to initiate nighttime sleep. Sleep loss impairs alertness and leads to poor performance (Wyatt, 2001). Not only can it impair alertness, sleep deprivation can lead to other cognitive impairments. For instance Roca, Fuentes, Marotta, Lopez-Ramon, Castro, Lupianez, & Martella (2012) was able to demonstrate that sleep loss impairs vigilant attention. Others (Killgore, Kahn-Greene, Lipizzi, Newman, Kamimori, & Balkin, 2008; Kim, Kim, Park, Choi & Lee, 2011) have observed impairments to problem-solving, inhibitory control, and decision-making associated with sleep loss. It is evident that sleep deprivation affects many cognitive domains. Therefore, it is important to understand how sleep deprivation influences the underlying mechanisms responsible for cognitive performance.

Sleep Deprivation and Cognition

General cognition. A literature review on the effects of short-term sleep loss concluded that sleep deprivation has detrimental effects on simple attention tasks, complex attention tasks, processing speed, and working memory (Lim & Dinges, 2010). According to Lim and Dinges (2010), each of these task categories requires unique processing resources. Simple attention tasks involve visual detection of a single stimulus with no perceptual discrimination, orienting or inhibition. Complex attention tasks require selection, but do not include major working memory components. Tasks that measure processing speed require multiple repetitions of a rehearsed process. Lastly, working memory tests are those that require the maintenance or manipulation of relevant information. The largest effects of sleep deprivation were on vigilance and simple attention tasks. Complex attention and working memory were less affected by sleep deprivation (Lim & Dinges, 2010).

Different types of sleep deprivation may have diverse effects on working memory. Drummond, Anderson, Straus, Vogel, and Perez (2012) administered a task to sleep deprived volunteers to assess their ability to ignore stimuli. An array of six coloured squares would appear in multiple locations followed by an image with either the identical number of squares or only one of the squares. Participants were instructed to determine if the image was the same or different from the original image. The participant had to identify if the one square was the same colour and in the same location, while ignoring the other squares, as part of the filtering task. The visual working memory component of the task was measured by the formula K= S(H-F). S is stimulus set size (4, 6, or 8 squares), H is hit rate, and F is false alarm rate. Full sleep deprivation (24 hrs without sleep) impaired performance on the filtering component but not on the visual working memory component. Four nights of partial sleep deprivation did not influence the visual working memory or the filtering component. The lack of influence on the filtering component could be due to partially sleep deprived participants experiencing reduced REM and N3 sleep, whereas fully sleep deprived participants had no REM and short wave sleep (SWS). Thus, partial sleep deprivation does not impair cognition in the same way as full sleep deprivation.

Thomas et al. (2000) used positron emission tomography (PET) to determine the neural effects of sleep deprivation on alertness and cognitive performance. After 24 hrs of sleep deprivation a significant decrease in global glucose was observed in the prefrontal cortex, posterior parietal cortex, thalamus and subcortical structures. Concurrently, performance on the Multiple Sleep Latency Test (MSLT) revealed that, after sleep deprivation, latency to N2 declined relative to a baseline (i.e., normal sleep). The MSLT was designed to provide information on sleepiness by measuring the speed of falling asleep and the presence of REM**.** The authors used the serial addition/subtraction task wherein two single digits and an operator (+ or –) appeared sequentially. If the operator was positive, participants entered the digit to the right of the answer (e.g., "8" is the answer to the sum "18"). If the operator was negative, then they added 10 and entered the resulting positive single digit. Accuracy on the cognitive task (the serial addition/subtraction task) declined by 3% and mean reaction time (RT) slowed by 13% compared to performance before sleep deprivation. These findings suggest that sleep deprivation impairs higher-order cognitive performance and reduces metabolic rate of glucose in fronto-parieto-thalamic networks.

Lamond and Dawson (1999) compared the performance of those who were sleep deprived to those with a blood-alcohol level of 0.1% on a number of cognitive tasks (i.e., a simple sensory comparison task, an unpredictable tracking task and a vigilance task). The simple sensory comparison task is a task wherein participants focused on a fixed spot for 750ms. Following this, a stimulus appeared in one of three squares. Participants responded by identifying the square that occupied the stimulus. The unpredictable tracking task is one that uses a joystick. Participants used the joystick to center a cursor over a moving target. Lastly, the vigilance task required participants to press one of six black buttons if one light appeared. If two lights appeared, then a separate red button was to be pressed. Performance decreased on these tasks after 28 hrs of sleep loss. This performance decrement was similar to the performance decrement that occurred with a blood alcohol level of 0.1%. This suggests sleep deprivation affects performance in a way that is similar to the effect of alcohol consumption on performance.

Vigilance/sustained attention. As previously stated, sleep deprivation affects many cognitive domains, especially attention (Lim & Dinges, 2010). There are many domains of attention, including *sustained attention*. Sustained attention refers to the process where a person is focusing their attention on a specific stimulus over a long period of time (Dawson and Medler, 2013). Other researchers have defined sustained attention as the ability to monitor and detect signals over a prolonged period and the state of readiness to respond to an unpredictable signal (Sarter, Givens, & Bruno, 2001).

Sustained attention is not necessarily vigilance. *Vigilance* refers to a "general state of wakefulness" (Lal & Craig, 2001, p. 177). Vigilance has also been suggested to reflect an ability to detect stimuli while in a state of fear or anxiety (Davis & Whalen, 2001). According to Oken, Salinsky, and Elsas (2006) *alertness* is equivalent to vigilance and sustained attention. Vigilance, alertness and sustained attention generally reflect the alignment of attention to a stimulus. Tasks that measure vigilance require the detection of stimuli presented sporadically in the presence of internal and/or external noise (Green & Swets, 1966; Jones, Smith, & Broadbent, 1979). Other vigilance tasks (e.g., the PVT; Basner, Mollicone & Dinges, 2011) are short (10 min), use a single stimulus that randomly appears at varying intervals (up to 10 s), and require a single response. There are a number of key PVT outcome measures: number of lapses (errors of omission; i.e., RTs over 500 ms), number of false alarms (i.e., errors of commission), and mean RT. Vigilance tasks that use an acoustic noise (e.g. Bakan vigilance task) may improve alertness and have the potential to enhance performance (Jones et al., 1979) and, therefore, they may not be an ideal test of vigilance. The PVT does not use acoustic noise and is unlikely to possess this confound. Thus, the PVT is an ideal task to use in sleep deprivation research.

Sleep Deprivation and Vigilance Measured by the PVT

It has been suggested that the PVT is sensitive to both homeostatic and circadian processes (Basner et al., 2011; Drummond, Bishoff-Grethe, Dinges, Ayalon, Mednick, & Meloy, 2005; Graw et al., 2004). Graw et al. (2004) had participants adjust their wake-sleep cycles so that the circadian pacemaker was measured separately from the homeostatic process. The low sleep pressure condition (i.e., the one assessing the circadian process) was analyzed after participants received 10 alternating cycles of 150 mins of wakefulness and 75 min naps. On the other hand, the high sleep pressure condition (i.e., the one assessing the homeostatic process) was analyzed after depriving participants of sleep over a 24 hr period. PVT performance was worse in the high sleep pressure condition than it was in the low sleep pressure condition, although performance in the low sleep pressure condition suffered as well. Graw et al. (2004) suggest that homeostatic and circadian processes both contribute to vigilance.

To further investigate the influence of sleep loss on vigilance, Loh, Lamond, Dorrian, Roach, and Dawson (2004) tested the validity of the 5 min PVT relative to the 10 min version. The authors observed a significant deterioration of performance (i.e., increase in mean RT, lapses, slowest RTs, and fastest RTs) following a night of no sleep on the 10 min and 5 min PVT. However, the performance decrement was less marked in the 5 min version than it was in the 10 min version. Thus, while the 5 min and 10 min PVT are both sensitive to sleepiness, the 5 min PVT may be less sensitive to sleepiness in some cases.

Basner et al. (2011) used two versions of the PVT (10 min and 3 min) to assess alertness after total sleep deprivation and partial sleep deprivation. In the total sleep deprivation condition, 24 participants remained awake for a 33 hr period. Each participant stayed in the lab for 5 days while performing a battery of tests (including the 10 min and the 3 min PVT) every 2 hrs. In the partial sleep deprivation condition, 47 participants remained in the lab for 12 days. Baseline measures were collected during the first 2 days of the 12 day protocol. During the subsequent nights, sleep was restricted to 4 hrs (the final 5 nights were conditions for another study and not analyzed). Basner et al. (2011) used 5 variables to measure and analyze performance outcomes on the PVTs: mean of 1/RT, slowest 10% of RTs, the number of lapses in the 10 min PVT (i.e., RTs over 500ms), the fastest 10% of RTs, and lapses in the 3 min PVT (RTs over 355ms, due to change in interstimulus interval).

Basner et al. (2011) observed faster RTs and an increase in errors of commission for the 3 min PVT compared to the 10 min PVT, in both the sleep deprived and baseline conditions. Performance deteriorated on both versions of the PVT following partial and total sleep deprivation. However, performance decrements were greater on the 10 min PVT than they were on 3 min version. It is important to note that the effect sizes were larger for all outcome measures in the 10 min PVT, than the 3 min PVT, for the total and partial sleep deprivation conditions. This suggests that the 10 min PVT is better suited than the 3 min PVT to capture the effects of sleep deprivation. It has been demonstrated that response speed and lapses on the PVT are particularly influenced by sleep deprivation (Basner et al., 2011). The PVT is an ideal task to study the effects of sleep deprivation on vigilance because of the rich matrix of outcome measures it provides. Thus, the PVT will be used in the current study for these reasons.

Sleep Deprivation and Resting/Active Electroencephalography (EEG)

In addition to evaluating vigilance through behavioural performance, other studies have examined the effects of sleep deprivation on EEG spectral frequencies (e.g., alpha, beta, theta) during wakefulness. Researchers have used EEG frequencies in order to quantify alertness (i.e., a dominant beta rhythm; Corsi-Cabrera et al., 1992; Hoedlmoser et al., 2011) and relaxed wakefulness (i.e., a dominant alpha rhythm; Akerstedt & Gillberg, 1990; Lorenzo et al., 1995; Verevkin et al., 2008). Although there are slight inconsistencies among reports of alpha change after sleep deprivation, alpha power tends to increase, when eyes are open, following sleep deprivation when compared to baseline for both active and resting-state recordings of EEG (Akerstedt & Gillberg, 1990; Corsi-

Cabrera et al., 1992; Lorenzo et al., 1995; Verevkin et al., 2008). Studies that use active-state EEG methods take segments of EEG that overlaps with a task (Corsi-Cabrera et al., 1996), whereas resting-state EEG methods evaluate frequency ranges over a period of time, usually 1 min, while participants are not engaged overtly in any task (Corsi-Cabrera et al., 1992). Active- and resting-state EEGs have their own advantages and disadvantages, yet resting-state may be best suited to study the effects of sleep deprivation. The stimuli in an active-state EEG study might act like warning signals, resulting in spikes of alertness. Methods that use resting-state EEG usually have participants keep their eyes open or closed for a short period of time. It is important to look at resting-state EEG when eyes are open as well as eyes closed due to the suppression of alpha frequencies with light exposure or visual stimuli when eyes are open (Berry et al., 2007).

Another common discrepancy among reports of alpha is that researchers calculate EEG power differently. There are two common ways to calculate EEG power: relative power and absolute power. Absolute power is simply the average EEG activity within one particular band (e.g., alpha, 8 Hz-12 Hz). Relative power is determined by dividing the power of one band (e.g., alpha) and by the combined total amount of all the other bands (e.g., delta, theta, and beta) (Pivik, et al., 1993). Although relative power controls for nonspecific changes to all frequencies, it lacks in the ability to precisely identify which EEG band contribute to the change. However, absolute power provides measures independently of one another and changes amongst bands can be readily identified.

Table 1 provides a summary of research that has measured alpha following sleep deprivation. For example, Akerstedt and Gillberg (1990) recorded resting-state EEG (open and closed eyes) before and after 17 hrs of sleep deprivation. Although there are some individual differences, the majority of participants in this study showed an increase in alpha following sleep deprivation when they had their eyes open. In contrast, Lorenzo, et al. (1995) had participants remain awake for 40 hrs. PVT and resting-state EEG were recorded following sleep loss (the EEG was recorded after the PVT). They reported a global increase in beta, theta and delta EEG power after sleep deprivation relative to baseline; however, alpha was the only EEG band that decreased (eyes open) after sleep deprivation.

Conversely, the study by Verevkin et al. (2008) had participants remain awake for 25 hrs. Resting-state EEG was collected every 3 hrs. While the EEG was recorded, participants were instructed to keep their eyes open and closed for a minute each resulting in a 4 min session. Within occipital locations, when the eyes were open, alpha activity increased after sleep deprivation. However, no significant increase was observed for eyes closed in later sessions. Similarly to occipital locations, frontal sites showed an increase in alpha activity in the last session when eyes were open compared to early sessions. Interestingly, alpha activity also increased when eyes were closed in the last session compared to earlier sessions.

Table 1. Summary of research showing increase/decrease changes in alpha frequencies after sleep deprivation.

Authors	Location	Alpha	Active/Rest	Power
Hoedlmoser et al., (2011)	Occipital	↔ No change in alpha from the first session to the last session.	Active, EEG recording during the PVT	Absolute
Verevkin et al., (2008)	Frontal & Occipital	↑ Alpha for eyes open (occipital and frontal) ↔ No change in alpha for eyes closed (occipital) ↑ Alpha for eyes closed (frontal)	Resting, EEG recording during eyes open/closed	Relative
Lorenzo et al., (1995)	Central	↑ Alpha 1 and 2 for eyes open ↓ Alpha 1 and 2 for eyes closed	Resting, EEG recording during eyes open/closed	Absolute
Corsi-Cabrera et al., (1996)	Central	↔ No increase or decrease for alpha 1 and 2	Active, EEG recording during the PVT	Relative
Akerstedt and Gillberg (1990)	Central, Temporal & Occipital	↑ Alpha 2 for eyes open (absolute) ↔ No change in alpha for eyes closed (absolute) ↓ Alpha 1 and 2 for eyes open (relative power)	Resting, EEG recording during eyes open/closed	Relative vs. Absolute
Corsi-Cabrera et al., (1992)	Central & Occipital	↑ Alpha for eyes open ↔ No change in alpha for eyes closed	Resting, EEG recording during eyes open/closed	Relative

Verevkin et al. (2008) also observed that higher scores of "daytime wake ability," and low scores on "morning lateness" (i.e., the level of morning sleepiness/wakefulness), predicted greater alpha power when the eyes are closed.

To determine if performing a task influenced alpha power outcomes, Corsi-Cabrera et al. (1992) compared EEG recordings taken the morning before sleep deprivation to EEG recorded after. The absolute power of alpha (with eyes open) increased after sleep deprivation but the relative power of alpha (eyes open) decreased after sleep deprivation. However, the researchers were unable to link sleep deprivation with cognitive deterioration normally found after sleep deprivation. The current work will address this issue by measuring resting-state EEG and PVT performance within the same session.

Corsi-Cabrera et al. (1992) recorded resting-state EEG before and after sleep deprivation. The researchers also contrasted their findings using absolute and relative power. Corsi-Cabrera et al. recorded EEG during eyes open and eyes closed protocols in the morning (between 7:00 a.m. and 9:00 a.m.) and at night (between 9:00 p.m. and 11:00 p.m.) before and after sleep deprivation and sleep. Participants were in sleep deprivation and full sleep conditions with multiple weeks between testing sessions (i.e., a within-subject experimental design). Resting-state EEG was recorded over central, temporal, and occipital sites. *Absolute power* in the alpha frequency band was unaffected by sleep deprivation when the eyes were closed. In the eyes open condition there was greater alpha, beta, theta, and delta absolute power the morning after sleep deprivation compared to the morning after a full night of sleep. In contrast, *relative alpha power* (eyes open) decreased the morning after sleep deprivation compared to the morning after a full night's sleep. Additionally, there was some evidence that sleep deprivation weakened interhemispheric transfer during the resting state. However, a weaker correlation between hemispheres, and a greater correlation within the same hemisphere, was observed following sleep deprivation (Corsi-Cabrera et al. 1992). No cognitive assessment was made during testing; therefore it is not clear how these EEG spectral power effects tie into the cognitive changes normally associated with sleep deprivation.

Overall, the literature on the effect of sleep deprivation on resting state EEG is inconsistent. However, different authors report different forms of testing (i.e. active or resting state EEG) as well as different methods of calculating EEG power (absolute and relative). This makes it difficult to determine how alpha is generally affected by sleep deprivation. Therefore, further research is needed to understand the effects of sleep deprivation on resting-state EEG.

Sleep deprivation, EEG, and the PVT

To understand the neural mechanisms involved in stimulus processing during sleep deprivation, Hoedlmoser et al. (2011) compared tonic (frequency power/event-unrelated) and phasic (event-related) EEG. Tonic EEG (alpha, beta, delta and theta frequencies) and phasic event related potentials (ERPs) (P1 and N1) were measured during the PVT. For the sleep deprivation condition, 20 participants woke at 7:00 a.m. and remained awake until 7:00 a.m. the next day. Every hour, from 11:30 p.m. to 6:30 a.m., the PVT was administered. Performance on the PVT after sleep deprivation resulted in slower RT and more lapses. The primary measure of phasic ERP was the P1. The P1 is a positive-going ERP component that peaks between 70 ms and 130 ms following the appearance of the stimulus. The P1 is thought to be associated with visual processing (Saaverdra & Bougrain, 2012). P1 amplitude decreased after sleep deprivation, while EEG delta and theta power over occipital regions increased after sleep deprivation (alpha revealed only a statistical trend). The researchers suggested that the decrease in P1 was related to lowered cortical arousal and attention during prolonged wakefulness. Additionally, the researchers suggested that increased delta resulted in poor cognitive performance and that tonic and phasic EEG elements represent different aspects of the same oscillatory activity (Hoedlmoser et al. 2011).

To identify the effects of sleep deprivation on active EEG, Hoedlmoser et al. (2011) demonstrated an increase in delta power over occipital locations following sleep deprivation. Alpha power, however, did not change. The complication with the Hoedlmoser et al. (2011) findings is that they confounded sleep deprivation with the time-of-day effect. Resting-state EEG was recorded during the evening before sleep deprivation while resting-state EEG after sleep deprivation was recorded in the morning. Lower resting-state EEG power is generally seen in the morning (Briere, Forest, Chouinard, & Godbout, 2003). Also, Eriksen and Akerstedt (2006) were able to show that fatigue was elevated during the evening compared to the morning and they suggested that evening testing is in close proximity to the part of the circadian cycle that promotes sleep.

Thus, Hoedlmoser et al.'s (2011) failure to observe an effect of sleep deprivation on alpha power may be due to a time-of-day decrease in alpha offsetting the increase in alpha resulting from sleep deprivation.

Similar to Hoedlmoser et al. (2011), other studies have also examined EEG frequencies (alpha, beta, theta and delta) while actively engaging in a task (see Corsi-Cabrera et al., 1996). Although, as mentioned previously, resting state EEG can be observed separately from the PVT to determine if sleep deprivation affects single or multiple underlying mechanisms.

Present research

The primary purpose of this study is to assess the effects of sleep deprivation on vigilance (the PVT, in particular) and tonic EEG frequencies. Previous studies have observed performance decrements on the PVT and increases in EEG frequencies (alpha, delta, and theta; see Lorenzo et al., 1995; Hoedlmoser et al., 2011; and Verevkin et al., 2008) following sleep deprivation. The current study is designed to measure the effects of full sleep deprivation on tonic EEG during a resting state. However, unlike other studies (e.g., Verevkin et al., 2008), this study is designed to link PVT performance with resting-state EEG after sleep deprivation. Both resting-state EEG and PVT are sensitive to sleep deprivation. By correlating the PVT and resting EEG frequencies (alpha, beta and theta) on Day 2 for both the sleep and sleep deprivation conditions, the current study has the potential to determine which frequency bands (i.e., alpha, beta or theta) are associated with vigilance decrements associated with sleep deprivation.

The 10 min PVT task will be used because the shorter versions of the PVT appear to be less sensitive to sleep deprivation (Basner et al., 2011). As Basner et al. note, some measures of the PVT are more sensitive to sleep deprivation than others. Responses from the slower end of the RT distribution (e.g., lapses, 10% slowest RT, and 1/RT) are particularly more sensitive to sleep deprivation than the mean RT (Basner et al., 2011). The ex-Gaussian model (Lacouture & Cousineau, 2008) will be used to fit the distribution of RTs from the PVT. Other studies have used other descriptive summaries of PVT performance (e.g. mean 1/RT), which may be insensitive to sleep deprivation. Doran, Van Dongen, and Dinges (2001) demonstrated that sleep deprivation affected the slowest RTs on the PVT. Faster responses, however, appeared "normal," suggesting that mean RT might obscure the effects of sleep deprivation on the PVT. The ex-Gaussian is the convolution of a Gaussian and exponential probability density functions. The ex-Gaussian approach offers a solution to this issue by capturing three parameters that can describe a positively skewed RT distribution. It is the convolution of a Gaussian and exponential probability density functions. Parameters from the Gaussian component (i.e. μ and σ) are separated from the one in the exponential tail (i.e. τ) (Lacouture and Cousineau, 2008). It is anticipated that sleep deprivation will affect the exponential parameter (i.e. τ) without influencing the Gaussian parameters (μ or σ). Interested readers can visit Lacouture and Cousineau (2008) for a full description of the ex-Gaussian.

Previous investigations of sleep deprivation have compared performance and other measures following sleep within the lab to wakefulness in the lab. Given the well-known effect of the so-called “first night” effect (i.e., the difficulty of falling asleep and the poor quality of sleep often seen in a novel environment; Agnew et al., 1966; Le Bon et al., 2001), many of these studies may have underestimated the consequences of sleep deprivation due to poor methods. Thus, in the current study, participants were sent home with a portable EEG system (Zeo) to record sleep in their natural sleeping environment.

Methods

Participants

Thirty-four participants aged 18-30 from both the public and students at Saint Mary's University were initially enrolled in this study. However, 11 of the 34 participants either dropped out of the study due to scheduling conflicts or they did not follow instructions properly resulting in their removal from the study (i.e. did not get a full night of sleep prior to testing or record sleep at home). In total, the data from 23 adults were included in this study. Within the full sleep condition there were 12 participants (randomly assigned): 5 males and 7 females. In the sleep deprivation condition 11 participants (randomly assigned): 7 males and 4 females. Participants were recruited from the psychology online bonus system (SONA) and through posters posted around campus. Participants were compensated $100CAD and 5 bonus points for completion of the study. Several criteria were used to limit the degree to which extraneous variables increase systematic variability in the sample

No caffeine. Caffeine consumption is known to improve attention, reaction time, working memory and sentence verification accuracy performance (Roehers & Roth, 2008; Rogers, Heatherley, Hayward, Seers, Hill, and Kane, 2005). Moreover, caffeine reduces total sleep time, reduces N3 and N4 sleep, and increases sleep latency, but has no effect on REM sleep (Roehers & Roth, 2008). Thus, participants in this study were asked to refrain from consuming caffeine (including energy drinks) 24 hrs before testing and during testing.

Medications. Participants were asked if they were on any medications that could affect alertness (including over the counter medication). Participants on any medication were excluded.

Non-Smokers. According to Lavigne, Lobbezoo, Rompre, Nielsen, and Montplaisir (1997) nicotine has been associated with cortical arousal, problems falling asleep, staying asleep, and daytime sleepiness. Thus, smokers were not allowed to participate in the study.

Alcohol. Participants in this study were asked to abstain from consuming any alcoholic beverages 24 hours before testing and for the duration of the study to avoid any influence on sleep.

Birth control. According to Genzel et al. (2012), women show a decrease in alpha, beta, theta and delta EEG power during the menstrual phase of their cycle. Additionally, Hatta and Nagaya (2009) demonstrated that sex-related hormones (in women) influence cognitive performance. For example, the Stroop performance of women with regular menstrual cycles (i.e. those not on any oral contraceptives) would fluctuate depending on their cyclic levels of estradiol and progesterone. Thus, to avoid any extraneous influence on the EEG recordings and behavioural performance, female participants were on birth control prior to testing. Female participants were scheduled to participate in the study 10 days after the last menstrual phase of their cycle.

Naps. Participants were asked to avoid napping throughout the day for the duration of this study, especially the day before the sleep or sleep deprivation condition.

Fitness level. Kohatsu et al. (2006) conducted a cross-sectional analysis of data from adults in Iowa. In their study, the BMI of volunteers was calculated and ranged from 28 to 30. They noted that high levels of BMI were correlated with short sleep durations. Due to the potential influence of fitness and BMI on sleep, participants who reported low-levels of fitness and had a BMI between 18-30 were excluded. Every participant was interviewed to determine eligibility. To ensure that all participants met the criteria participants were given three fitness-based surveys: the Exercise Readiness Questionnaire (ERQ) (ExRx.net LLC, 1999); the Physical Activity Readiness Questionnaire (PAR-Q) (Physical Activity Readiness Questionnaire-PAR-Q, 2002); and the International Physical Activity Questionnaire (IPAQ) (Long last 7 day self-administered, 2002). The ERQ quantifies the general physical health level of respondents. The PAR-Q assesses the degree to which someone is physically active. A moderate score is 3 or more days of 20 min of vigorous activity. A high score is vigorous intense activity lasting 3 days. While a low score of physical activity is less than 3 days of activity. Finally, the IPAQ is a questionnaire on physical health conditions that could prevent regular physical activity. Those that answered “yes” to any health concern items on the ERQ and PAR-Q were unable to participate in the present study. Also, those that did not score a medium to high level of fitness score on the IPAQ were disqualified from the study. A total of 5 participants were excluded for not meeting the criteria.

Apparatus

Zeo. The bedside device by Zeo Inc. (Newton, MA) contains a headband with dry fabric sensors that transmit real time signals wirelessly to a device that is placed nearby. The bedside device provides a summary of total time in REM sleep, light sleep, deep sleep, and awake. To address the accuracy of the Zeo bedside device, Shambroom, Fabregas, and Johnstone (2012) conducted a study that compared the recordings from the Zeo device to those from standard polysomnography and actigraphy. The Zeo wireless headband was able to capture a signal at 128 samples per second and the bedside device was able to calculate the signals in real time. Results suggested that the Zeo was able to provide a 75%-85% agreement with polysomnography when reporting staging of sleep.

EEG. An EGI 32 electrode Hydro Cel Geodesic Sensor Net from Electrical Geodesic Inc. (Eugene, OR). was used and held in place by an elastic cap. The EEG ran a net amp with 250 Hz samples per second. Impedance values less than 50 µV were acceptable and amplitude sensitivity was set at 10 µV per minute. Data was filtered with a high pass 0.1Hz filter and a low pass filter of 30Hz and referenced to the electrode Cz. Eye blinks and artifacts were filtered and removed using NetStation.

Procedure

In this study, participants in both the sleep and sleep deprivation conditions partook in 2 days of testing. The first day assessed baseline performance on the PVT and assessed baseline EEG frequencies. The second day assessed the effects of sleep deprivation on performance and EEG frequencies. During Day 1 and Day 2 of testing, participants were asked to arrive at the laboratory prior to 10:00 a.m. Testing started at 10:00 a.m. for both days and ended, on average, around 12:00 p.m. After participants completed Day 1 they were instructed to return to the lab at 8:00 p.m. (the same day) to be randomly selected and placed in either the full sleep condition or the sleep deprivation condition. If participants were randomly selected for the full sleep condition, they returned home and slept in their own bed for 7-8 hrs. Those in the sleep condition were instructed to return back to the lab at 10:00 a.m. for Day 2 of testing. If participants were randomly assigned to the sleep deprivation condition, then they remained in the lab with a research assistant. They spent the night awake until testing at 10:00 a.m. on Day 2. Participants in the sleep deprivation condition were awake for approximately 24 hrs. They were instructed to limit physical activity and they were instructed not to consume caffeine. Participants were also instructed not to consume heavy meals (e.g., pizza or burgers) during sleep deprivation. Prior to testing, a weeklong baseline of sleep behaviour was collected using the Zeo. The participants in both conditions brought the Zeo bedside device home to ensure that they were getting a full night of sleep (7-8 hrs) during the weeklong baseline.

During Day 1 and Day 2 participants were given the following tasks: PVT, a speed-accuracy tradeoff task[1] (SAT), and resting state EEG (rEEG). First, participants were given the PVT. After the PVT was completed, they were fitted with the geodesic

[1] Although data was collected on the SAT task, the data will not be described in this paper and will be analyzed for discussion in another report.

net. After the net was applied to the participant's head, rEEG was recorded for 4 min, alternating eyes open and closed. Following this task, the SAT was administered, then rEEG recording, SAT, and then a final rEEG recording. The geodesic net was then removed. After the EEG net was removed, the final PVT was administered.

PVT. Participants sat 57 cm away from a Dell 17" computer screen (with a resolution of 1280 by 960 pixels) in a dimly lit room. Participants were instructed to monitor a central red box (11 cm by 7 cm) with a black coloured background for a yellow counter stimulus (Font size of 32) (see figure 1). As soon as the counter appeared, participants were told to press the "n" button on the keyboard as fast as they could. After a response was made the counter would display their response time for 1 s. See Figure 1 for an illustration of the task stimuli. If a response was not registered before 30 s then the screen would clear and "OVERRUN" would be displayed for 1s. The response-stimulus interval was randomly determined, with a uniform distribution, between 2 s and 10 s. There were a total of 100 trials and the task lasted about 10 min. The PVT was administered twice, for a total of 200 trials.

Resting-state EEG task (rEEG). Participants sat in front of a computer and were instructed to have their eyes open while looking at a fixation cross on the screen. After 10 s, a 60 s epoch of raw EEG was recorded. Following this, participants closed their eyes and a 60 s recording resumed. This pattern is repeated once again. Participants were instructed to minimize blinking while their eyes were open. This task lasted approximately 5 min and was administered three times (3 blocks of 2 trials).

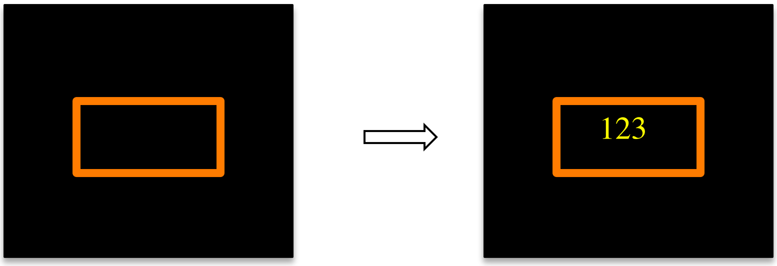

Figure 1. The psychomotor vigilance task where participants were instructed to respond when they saw the counter in the red box by pressing “n” on the keyboard.

Data Analysis

PVT. Many studies on the PVT analyze the data by comparing the fastest 10% and slowest 10% of response times (see Basner et al., 2011; Blatter, Graw, Munch, Knoblauch, Wirz-Justice, & Cajochen, 2006; Drummond et al., 2005;). Other studies use the inverse of the mean RT (i.e., 1/mean RT; see Graw, Werth, Krauchi, Gutzwiller, Cajochen, & Wirz-Justice, 2001). Basner and Dinges (2011) observed that the total number of errors (lapses and false starts) were maximally sensitive to sleep deprivation while most RT summary metrics (mean and median) were the least sensitive. However, Doran, van Dongen, and Dinges (2001) observed that sleep deprivation did not seem to have an effect on all RTs, but it did increase RT fluctuations. Thus, standard summary statistics may be insensitive to sleep deprivation. For this reason, the RTs were fitted to an ex-Gaussian distribution (Balota & Yap, 2011; Lacouture & Cousineau, 2008).

Resting-state EEG frequency bands. EEG data were sampled at 250 Hz per second, segmented in Netstation (Electrical Geodesics Inc., Eugene, OR) and extracted for further analysis using FieldTrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) in Matlab (The Mathworks, Natick, MA). The data were then segmented into four regions of interest: frontal (sites F3, Fz, and F4), central (sites C3, Cz, and C4), parietal (sites P3, Pz, and P4) and occipital (sites O1, Oz, and O2). The segmented data were filtered using a 0.1 Hz high pass filter and subjected to a fast independent component analysis (Hyvärinen, 1999) for detection and removal of ocular artifacts. EEG data were further parsed into 512 samples with a 100 ms Hanning window. FFT analysis was used to extract spectral frequencies across the windowed data. The mean FFT amplitudes were taken across windowed data. A log transform was performed on the following frequency components: alpha (8 Hz-12 Hz)[2], beta (15 Hz-35 Hz) and theta (4 Hz-8 Hz).

[2] A preliminary analysis was conducted on alpha 1 (8 Hz-10 Hz) and 2 (10 Hz-12 Hz) and the results were similar to alpha (8 Hz -12 Hz). Thus, alpha was not split into alpha 1 and alpha 2 even though there have been inconsistencies (see Gast et al., 2011; Hoedlmoser et al. 2011,) with alpha increasing and decreasing after sleep deprivation. However, most inconsistencies are not with alpha split into two but with alpha frequencies when eyes are open or closed (Akerstedt and Gillberg, 1990).

Results

Baseline of sleep. The data from the Zeo device were evaluated to determine whether participants had similar durations of light sleep, deep sleep, REM, and total time asleep prior to the study. The Zeo bedside device recorded each participant's quality of sleep 5-7 days prior to testing. The last 3 days of recorded sleep before Day 1 of testing were analyzed. Using the last 3 days instead of all days (7-8) ensured that there were an equal number of days across participants. Additionally, this eliminated the corrupted data that resulted from participants needing to adjust to wearing the Zeo headband. For instance, all participants reported that within the first couple of days the headband would fall off, resulting in lost data. Both sleep and sleep deprivation scores for deep sleep, light sleep, and REM sleep stages were compared using an independent sample t-test (see Table 2). There were no differences between the full sleep and sleep deprivation conditions in any of the Zeo sleep metrics (deep sleep, light sleep, REM sleep, or time awake) prior to testing. The data from one participant in the sleep deprivation condition were missing due to a device error.

Table 2. Zeo descriptive stats and t-test scores of sleep from all participants before testing.

Variable	*n*	Mean (min)	Std. Deviation	df	t-val.	p-val.
Deep sleep						
Sleep deprivation	10	71.732	28.246	20	-.555	.585
Sleep	12	77.917	24.034			
Light sleep						
Sleep deprivation	10	188.5	61.6	20	.068	.947
Sleep	12	186.78	57.37			
REM sleep						
Sleep deprivation	10	101.10	45.21	20	-.398	.695
Sleep	12	107.53	10.24			
Wake sleep						
Sleep deprivation	10	6.6	4.29	20	1.061	.301
Sleep	12	4.6	4.44			

PVT. Before statistical analysis was performed, the PVT data were adjusted for missing data points. There were 2 blocks of PVT trials during each day of testing. The data from the first block were missing for 4 participants due to file save errors (i.e., data in the first block were replaced by the data in the second block). Two participants were in the sleep deprivation condition and 2 participants were in the sleep condition. The missing data were replaced with the average of the 2 blocks (see Appendix A). A repeated measures ANOVA was performed separately for lapses, false alarms, μ, σ, and τ. Day (1, 2) and Block (1, 2) were the within-subject factors. Condition (full sleep and sleep deprivation) was the between-subject factor. There were 2 types of PVT errors. First, RTs that exceeded 500 ms were labeled as lapses. Second, RTs that occurred in the absence of the target (i.e., the stimulus counter) were identified as false starts. Individual RT distributions were fit to the ex-Gaussian and the parameter estimates (μ, σ, and τ) were derived using MATLAB functions provided by Lacouture and Cousineau (2008). The repeated measures ANOVAs were run without using the participants with missing data. Results of the analysis did not change when compared to results with the participant's data that was replaced by the second run. Due to the small sample size, the participants with missing data were included in the subsequent analyses.

The same repeated measures ANOVA conducted on the μ parameter revealed a main effect of Day ($F[1,21]= 12.313$, $p <0.01$). Likewise, the analysis of the σ parameter also revealed a main effect of Day ($F[1,21]=6.054$, $p<0.05$). However, this increase in μ and σ from Day 1 to Day 2 did not differ between the full-sleep and sleep deprivation conditions. Interestingly, the repeated measure ANOVA on τ revealed a different pattern. There was a significant main effect of Day in τ ($F[1,21]=5.842$, $p<0.05$) that was significantly modified by condition ($F[1,21]=8.289$, $p<0.01$). A paired sample t-test revealed that τ for the sleep deprivation condition increased from Day1 to Day 2, ($t[10]=-2.629$, $p<0.05$), whereas it did not change from Day 1 to Day 2 for the full sleep condition ($t[11]=0.888$, $p>0.05$) (see Figure 2).

A repeated measures ANOVA on lapses revealed a main effect of day that was significantly modified by condition, $F[1, 21]=6.773$, $p<0.05$. A paired sample t-test indicated that lapses in the sleep deprivation condition increased from Day 1 to Day 2, ($t[10]=-2.83$, $p<0.05$), while no change was observed in the sleep condition ($t[11]=-0.675$, $p>0.05$). There were no significant effects in the analysis of false starts (see Appendix A).

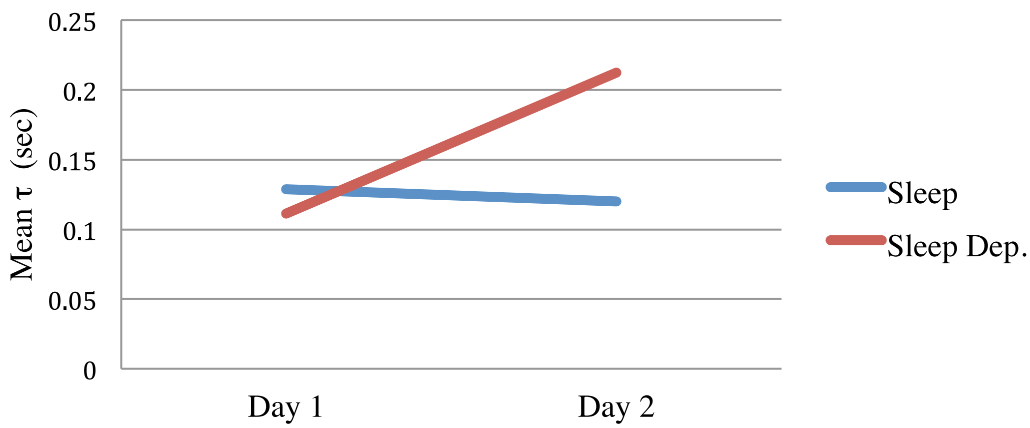

Figure 2. Mean τ from day one and two for the full sleep (Sleep) and sleep deprivation (Sleep Dep.) conditions.

rEEG absolute power. The goal of the rEEG analysis was to evaluate the spectral power of alpha, beta, and theta frequencies during the resting state. Raw EEG was pre-processed as described earlier. Two participants from the sleep condition and 2 participants from the sleep deprivation condition were missing data in one of the three blocks. Participants with missing data were removed from further analysis[3]. Previous research has found greater alpha power when the eyes are closed (Laufs et al., 2006: MacLean et al., 2012) within posterior sites (Laufs et al., 2006). Thus, repeated measures ANOVAs were conducted separately for each site when eyes were closed. Other studies have focused on alpha when eyes were open (see Corsi-Cabrera et al. 1996; Lorenzo et al., 1995; Verevkin et al., 2008) thus, repeated measures ANOVA was conducted for each site separately with eyes open. Repeated measures ANOVAs were performed separately on the four sites (frontal, parietal, central and occipital) and each frequency band (alpha, beta, and theta). Day (1, 2) and Block (1, 2, and 3) were the within-subject factors, and condition (full sleep and sleep deprivation) was the sole between-subject factor. Only the highest-order interactions involving day, block and condition are reported here for brevity.

Alpha. The analysis of spectral power for alpha frequencies when the eyes were closed revealed a significant interaction of Block, Day, and Condition only at occipital sites, ($F[2,34]=6.627$, $p<0.01$) (See Appendix B). Analysis of spectral power at frontal sites ($F[2,34]=1.772$, $p>0.05$), central sites ($F[2,34]=0.816$, $p>0.05$), and parietal sites

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[3] A repeated measures ANOVA on data that included participants with missing data (but included Block 1) indicated that there was no significant interaction between Condition, Block or Day in any of the EEG bands (i.e., alpha, beta, and theta). These results are similar to those observed when excluding participants with missing data.

(F[2,34]=1.408, p>0.05) revealed no significant interaction between Day, Group, and Condition. To break down the complex three-way interaction at the occipital sites, separate repeated measures ANOVAs (with Day and Condition as factors) were conducted for each Block. Analysis of spectral power at occipital sites for Block 1 revealed a significant interaction between Day and Condition (F[1,17]=8.838, p<0.01), with no significant interaction for Block 2 (F[1,17]=2.492, p>0.05) or Block 3 (F[1,17]=0.647, p>0.05). Furthermore, separate paired sample t-tests were performed comparing Day 1 and Day 2 for the sleep and sleep deprivation conditions for Block 1, eyes closed, and at the occipital sites. Interestingly, a significant decrease in alpha power from Day 1 to Day 2 for the sleep deprivation condition was observed (t[9]=5.313, p<0.01) (see Figure 3). On the other hand, there was no significant difference between spectral alpha power on Day 1 and Day 2 for the sleep condition (t[10]=0.742, p>0.05). The analysis of spectral power for alpha frequencies when the eyes were open revealed no significant interaction of Block, Day and Condition at occipital sites (F[2,34]=2.182, p>0.05), frontal sites (F[2,34]=2.093, p>0.05), central sites (F[2,34]=0.410, p>0.05), or parietal sites (F[2,34]=1.058, p>0.05).

Beta. The analysis of spectral power for beta frequencies when the eyes were closed revealed no significant interaction between Block, Day and Condition within occipital sites, (F[2, 34]=2.199, p>0.05). Complete ANOVA tables are presented in Appendix C. Analysis of spectral power at frontal sites (F[2,34]=1.367, p>0.05), central sites (F[2,34]=1.672, p>0.05) and parietal sites (F[2,34]=1.439, p>0.05) also revealed no significant interaction. The analysis of spectral power for beta frequencies when the eyes were open revealed no significant interaction of Block, Day, and Condition at occipital sites (F{2,34]=1.069, p>0.05), frontal sites (F{2,34]=0.195, p>0.05), central sites (F[2,34]=0.724, p>0.05) and parietal sites (F[2,34]=0.451, p>0.05).

Theta. Similar to the results found for beta, the repeated measures ANOVA for theta frequencies when the eyes were closed revealed no significant interaction between Block, Day, and Condition within occipital sites, (F[2, 34]=2.124, p>0.05). Complete ANOVA tables are presented in Appendix D. Analysis of spectral theta power at frontal sites (F[2,34]=1.309, p>0.05), central sites (F[2,34]=0.287, p>0.05) and parietal sites (F[2,34]=0.269, p>0.05) also revealed no significant interaction. The analysis of spectral power for theta frequencies (eyes open) revealed no significant interaction of Block, Day, and Condition at occipital sites (F[2,34]=1.068, p>0.05), frontal sites (F[2,34]=0.955, p>0.05), central sites (F[2,34]=0.317, p>0.05) and parietal sites (F[2,34]=0.037, p>0.05).

rEEG ratio power. The goal of the rEEG ratio analysis was to evaluate spectral power of alpha, beta, and theta frequencies during the resting state as a function of beta and theta power. Two participants from the sleep condition and 2 participants from the sleep deprivation condition were missing data in one of the three blocks. Participants with missing data were removed.

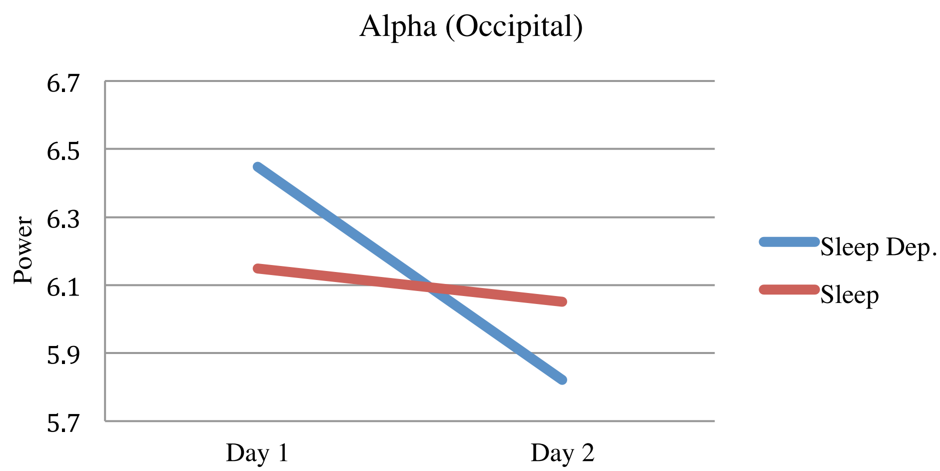

Figure 3. Comparing alpha power for Block 1 when the eyes were closed from Day 1 and Day 2 for the full sleep (Sleep) and sleep deprivation (Sleep Dep.) conditions.

Repeated measures ANOVAs were performed on the 4 electrode sites (frontal, parietal, central and occipital) for each ratio frequency (alpha:theta and alpha:beta) with Day (1/2) and Block (1,2, and 3) as within-subject factors. Condition (full sleep and sleep deprivation) was the only between-subject factor. Complete ANOVA tables are presented in Appendices E (alpha:beta) and F (alpha:theta). Only the highest-order interactions involving Day, Block, and Condition are reported here.

Alpha:Beta. The analysis of spectral power for alpha:beta[4] frequencies when the eyes were closed revealed no significant interaction at occipital sites (F[2,34]=0.105, p>0.05), frontal sites (F[2,34]=0.410, p>0.05), central sites (F[2,34]=0.872, p>0.05), and parietal sites (F[2,34]=0.847, p>0.05). The analysis of spectral power for alpha:beta frequencies when the eyes were open revealed no significant interaction at occipital sites (F[2,34]=0.071, p>0.05), frontal sites (F[2,34]=0.058, p>0.05), central sites (F[2,34]=0.875, p>0.05), and parietal sites (F[2,34]=1.170, p>0.05).

Alpha:theta. The analysis of spectral power for alpha:theta (Alpha/theta) frequencies when the eyes were closed revealed no significant interaction at occipital sites (F[2,34]=1.478, p>0.05), frontal sites (F[2,34]=2.932, p>0.05), central sites (F[2,34]=0.193, p>0.05), and parietal sites (F[2,34]=1.301, p>0.05). The analysis of spectral power for alpha:theta frequencies when the eyes were open revealed no significant interaction at occipital sites (F[2,34]=0.787, p>0.05), frontal sites (F[2,34]=0.374, p>0.05), central sites (F[2,34]=0.152, p>0.05), and parietal sites

[4] A repeated measures ANOVA on the data that included participants with missing data (but excluded Block 1) indicated no significant interaction between Condition, Block and Day for alpha:beta ratios. These results are similar to results found when statistics were ran excluding participants with missing data.

($F[2,34]=0.640$, $p>0.05$). However, when an analysis of spectral power for alpha:theta was conducted including the participants with missing data (excluding Block 1 that had the missing data points) a significant interaction was found at frontal sites ($F[1,21]= 6.123$, $p<0.05$) when the eyes were closed (see Appendix G). Also, no significant interactions were observed at central sites ($F[1,21]=0.431$, $p>0.05$), parietal sites ($F[1,21]=0.001$, $p>0.05$), and occipital sites ($F[1,21]= 2.017$, $p>0.05$). Additionally, when the eyes were open, no significant interactions were found at frontal sites ($F[1,21]=0.009$, $p>0.05$), central sites ($F[1,21]=2.618$, $p>0.05$), parietal sites ($F[1,21]=0.723$, $p>0.05$), and occipital sites ($F[1,21]=0.006$, $p>0.05$). To break down this complex two-way interaction when eyes are closed, separate repeated measures ANOVAs (with Day and Condition as factors) were conducted for each Block. A significant interaction was found for Block 2 ($F[1,21]= 11.587$, $p<0.05$). There were no interactions found for Block 3 ($F[1,21]= 3.599$, $p>0.05$). A paired sample t-test was conducted indicating a significant alpha:theta ratio spectral power decrease form Day 1 to Day 2 for the sleep deprivation condition for Block 2 ($t[10]= 5.082$, $p<0.01$). Furthermore, there was no significant alpha:theta ratio spectral power difference between Day 1 and Day 2 for the sleep condition for Block 2 ($t[11]=0.678$, $p>0.05$).

Correlations. The non-parametric Spearman's ρ was used to assess correlations between variables. The relationship between pre-testing of sleep quality (as measured with the scores from the Zeo device), the PVT scores (specifically τ**),** and the absolute alpha power values of the rEEG (at occipital site, when the eyes were closed) was assessed for both sleep deprived and full sleep groups combined. No correlations were statistically significant (See appendix H). However, there was a correlation between light sleep and the first block of τ on day 2.

Given the interaction on Day 2 for the sleep deprivation condition, the ex-Gaussian metric τ from the PVT and the alpha power (occipital, eyes closed) rEEG were significant, the relationship between theses individual interactions was explored on Day 1 and Day 2 for both the sleep and sleep deprivation conditions. The correlation was not significant for the full sleep or the sleep deprivation group. Furthermore, the correlation between Day 1 and Day 2 (i.e. Day 2 – Day 1) for τ and alpha absolute power (eyes closed, occipital) was not significant for the full sleep group or the sleep deprived group (See appendix I).

General Discussion

It has been previously demonstrated (e.g., Basner et al., 2011; Hoedlmoser et al., 2011) that PVT performance deteriorates after sleep deprivation. Specifically, slower RTs and more lapses occur. Additionally, resting-state EEG spectral power (especially alpha frequencies within posterior sites) increases with eyes open following sleep deprivation (Corsi-Cabrera et al. 1996; Lorenzo et al., 1995; Verevkin et al., 2008) and decreases when the eyes are closed (Laufs et al., 2006; MacLean et al., 2012).

The current study revealed that the exponential component of the ex-Gaussian (τ) fit to the RTs from the PVT task increased after sleep deprivation. Also, a significant increase in lapses on the PVT from Day 1 to Day 2 was seen in the sleep deprivation condition while no such change was observed in the sleep condition. This demonstrates that sustained attention was affected by sleep deprivation. Concurrently, the results for μ, σ and false starts yielded no significant differences between the sleep deprivation and the sleep conditions. However, μ and σ increased from Day 1 to Day 2 for those who were sleep deprived and those who had a full night's sleep. These findings highlight that not all PVT outcome measures suffer following sleep deprivation (e.g. μ and σ).

The increase in the exponential component (τ) and lapses for the sleep deprivation condition on Day 2 is consistent with the literature. For instance, Graw et al. (2004) observed an increase in lapses from the baseline for both fully and partially sleep deprived groups. However, the fully sleep deprived group had more lapses than the partially sleep deprived group. Graw et al. also observed a slowing of the slowest RT (the

90th percentile) after sleep deprivation. Additionally, Graw et al. were able to demonstrate that full or partial sleep deprivation had no effect on false starts. Similarly, this study also found no effect of sleep deprivation on false starts.

The results from this study showed that sleep deprivation increased the exponential component (τ), providing some support for the idea that sleep deprivation increases the sleep initiating mechanisms that cause performance fluctuations resulting from an unstable attention state (Doran et al., 2001). According to this state-instability hypothesis, sleep deprivation does not necessarily "impair" performance; it simply makes performance increasingly variable. The ex-Gaussian approach, however, pinpoints the effect of sleep deprivation to the tail of the RT distribution. However, it is not clear what mechanism is responsible for the difference between Day 1 and Day 2 on the parameters of the Gaussian component of the RT distribution.

According to Boksem, Meijman, and Lorist, (2005; see also Mun, Kim, & Park, 2014), mental fatigue is evident when one has difficulties concentrating and focusing attention on relevant information. The effects of mental fatigue are sometimes greater under conditions of sleep deprivation (Asplund & Chee, 2013). Mental fatigue occurs when engaged on a particular task over a prolonged period of time. It is tempting to speculate that mental fatigue, rather than sleep loss, influenced performance on the PVT. If mental fatigue influenced performance on the PVT, it should appear as an effect of Block in the analysis. However, this was not observed. Breaks and new tasks tend to eliminate, or severely reduce, the effects of mental fatigue (Hockey, 2011). Thus, the increase in the Gaussian parameters (i.e., μ and σ from the ex-Gaussian analysis of RT), on Day 2 is unlikely to reflect mental fatigue. Importantly, the exponential parameter, τ, only increased on Day 2 in the sleep deprivation group. Thus, mental fatigue is unlikely to have played much of a role in the increase observed in the exponential component (τ).

Alpha frequencies are most commonly observed when a person is in a relaxed but awake state of alertness (Lavie, 1993). Absolute alpha spectral power decreased in posterior (i.e., occipital) sites from Day 1 to Day 2 in the sleep deprivation condition, when the eyes were closed. Additionally, the alpha:theta ratio decreased within frontal sites (when eyes are closed) from Day 1 to Day 2, suggesting that all of the other frequency bands were not contributing to this decrease. However, this was only observed when adding participants with partial data (i.e., those missing some blocks of data). No significant change was observed in alpha when eyes were open or in any other region. Furthermore, the current results revealed no significant interaction between Day and Condition for beta or theta power with the eyes open or closed. The decrease in alpha may reflect a general decrease in subcortical arousal and a strong motivation for sleep (Strijkstra, Beersma, Drayer, Halbesma, & Daan, 2003).

The study by Laufs et al. (2006) was designed to address patterns describing the relationship between BOLD signals and alpha power. Participants kept their eyes closed while resting during two 20 min sessions while fMRI and EEG were recorded. Laufs et al. (2006) observed an inverse correlation between alpha and beta power such that in occipital-parietal sites when alpha increased, beta decreased. It was also found that theta increases correlated with increased BOLD signals at occipital and parietal regions. Similar to Laufs et al. (2006), the current results demonstrated a decrease in alpha when the eyes were closed within occipital sites. Unlike Laufs et al. there was no corresponding greater increase in beta. This discrepancy may have be the result of differences in the length of the resting-state testing protocol (i.e., 6 min in the current study versus 20 min in Laufs et al., 2006). The current findings are more in line with Lorenzo et al. (1995) who observed a decrease in alpha when eyes were closed after sleep deprivation with shorter (<30 sec) testing durations.

Although sleep deprivation reduced rEEG alpha and slowed the slowest RTs (i.e., increased the τ parameter from the ex-Gaussian analysis of the RT distribution) in the PVT, these two effects did not significantly correlate. This suggests that sleep deprivation independently affects more than one underlying neurocognitive mechanism. However, it is also possible that the analysis lacks the statistical power necessary to detect a correlation.

The current results were similar to previous findings; however, the results diverge from those of other studies in a few interesting ways. Recall that less alpha power after sleep deprivation than after a full night's sleep was observed. Other studies on sleep deprivation found that alpha power, when eyes were closed, did not change. For instance, Corsi-Cabrera et al. (1992) found no change in alpha power with an eyes closed protocol. However, these authors used the same participants for both the sleep and sleep deprivation conditions. Corsi-Cabrera et al., (1992) should have had sufficient statistical power to detect a change in alpha because of their within-subject design. Yet no effect was observed. Also, Corsi-Cabrera et al. (1992) assessed sleep quality prior to testing by having participants complete a questionnaire. Without quantitative assessment of sleep (such as polysomnography), baseline levels of alpha power are unknown.

Other studies have also failed to observe changes in alpha with sleep deprivation. Akerstedt and Gillberg (1990), and Verevkin et al. (2008), failed to observe a reduction in alpha (eyes were closed) in a sleep-deprived condition relative to a full-sleep condition. However, both studies used questionnaires to provide information about prior sleep history. Questionnaires do not necessarily provide adequate control or assessment of the quality of sleep prior to testing. These authors also used their first session data, out of multiple sessions given throughout the sleep deprivation period, as a baseline. By comparing session data at different day times these authors did not adequately control for potential circadian factors. In the present investigation, the resting state EEG task was administered in the morning before sleep deprivation and the following day to control for potential circadian factors. Also, the recording of sleep quality prior to testing assessed the influence sleep had on testing. Prior sleep (using the Zeo) patterns between our two groups did not differ in the quality or quantity of sleep prior to testing on day 1. There no correlation between the quality of sleep prior to testing, PVT scores, and rEEG power values. This suggests that the quality and quantity of sleep prior to testing did not influence the present results.

Although the Zeo is purported to be a reliable measure of sleep (Gumenyuk et al., 2011; Shambroom et al., 2011), polysomnography is the preferred device among researchers. The lack of a correlation between the quality of sleep and the PVT and rEEG may be due to poor sleep staging by the Zeo device. On the other hand, the lack of a correlation between these measures could imply that sleep deprivation has multiple effects on information processing. Future research should assess the quality of sleep prior to testing using standard polysomnography to determine if the quality of sleep prior to testing is correlated with performance and rEEG.

In summary, the present work is consistent with the literature demonstrating that sleep deprivation impairs vigilance by slowing even further the slowest RTs on the PVT. It adds support for the proposal that the presence of sleep initiating mechanisms cause performance fluctuations resulting from an unstable attention state (Doran et al., 2001). Moreover, the present results also demonstrated a decrease in alpha (when eyes were closed) suggesting an increase in general sleepiness and a greater motivation for sleep. The decline in alpha power and PVT performance with sleep deprivation may be unrelated, suggesting that sleep deprivation does not have a unitary effect on neurocognitive functioning.

Appendix A

Table A1. A repeated measures ANOVA analysis of the Psychomotor Vigilance tasks comparing sleep deprived and full sleep participants using Ex-Gaussian. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
μ				
Between subject				
Condition[a]	1, 21	.00	.083	.004
Within subject				
Day[b]	1, 21	.010	12.313**	.370
Block[c]	1, 21	.001	1.246	.056
Day * Condition	1, 21	.001	1.290	.058
Block * Condition	1, 21	.002	2.031	.088
Day * Condition	1, 21	.001	2.54	.108
Day * Block * Condition	1, 21	8.432	.016	.001
τ				
Between subject				
Condition	1, 21	008	1.951	.085
Within subject				
Day	1, 21	.012	5.842*	.218
Block	1, 21	.008	10.853**	.341
Day * Condition	1, 21	.017	8.289**	.283
Block * Condition	1, 21	.001	.987	.041
Day * Block	1, 21	.001	1.14	.051
Day * Block * Condition	1, 21	1.588	.221	.225
σ				
Between subject				
Condition	1, 21	3.362	.227	.011
Within subject				
Day	1, 21	.00	6.054*	.224
Block	1, 21	.00	2.469	.105
Day * Condition	1, 21	8.235	.000	.00
Block * Condition	1, 21	.00	4.629*	.181
Day * Block	1, 21	.00	1.795	.079
Day * Block * Condition	1, 21	6.02	.034	.043
False Start				
Between subject				

(continued)

Table A1. (continued)

Variable	df	MS	F	Partial η^2
Condition	1, 21	2.161	.86	.039
Block * Condition	1, 21	.033	.037	.002
Day * Block	1, 21	1.226	2.21	.095
Day * Block * Condition	1, 21	2.269	4.092	.163
Lapses				
Between subject				
Condition	1, 21	509.319	4.436*	.174
Within subject				
Day	1, 21	482.65	9.007**	.302
Block	1, 21	174.806	14.178**	.403
Day * Condition	1, 21	360.036	6.773*	.244
Block * Condition	1, 21	21.502	1.74	.077
Day * Block	1, 21	.775	.137	.006
Day * Block * Condition	1, 21	1.731	.306	.014

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented two times resulting in two blocks.

Table A2. Paired-sample t-test on τ comparing sleep deprived and full sleep participants for day 1 and day 2 and combing the two blocks.

Variable	df	Mean	Std. Deviation	t-val.
Sleep Deprivation				
Day 1 * Day 2	10	-0.101	.128	-2.629*
Sleep				
Day 1 * Day 2	11	.009	.034	.888

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

Table A3. Paired-sample t-test on lapses comparing sleep deprived and full sleep participants for day 1 and day 2 and combing the two blocks.

Variable	df	Mean	Std. Deviation	t-val.
Sleep Deprivation				
Day 1 * Day 2	10	-17.09	20.03	-2.830*
Sleep				
Day 1 * Day 2	11	-1.25	6.41	-0.675

*p<0.05. ** p<0.01. *** p<0.001

Table A4. Descriptive analysis of the PVT performance for sleep deprived and full sleep participants

Sleep condition					Sleep deprivation condition				
Block					Block				
	1		2			1		2	
Day 1	Mean	SD	Mean	SD	Day 1	Mean	SD	Mean	SD
μ	.2587	.0587	.2829	.0302	μ	.2777	.0239	.2827	.0248
τ	.0570	.0193	.0716	.0139	τ	.0490	.0141	.0620	.2510
σ	.0173	.0080	.0223	.0066	σ	.0234	.0078	.0186	.0075
FS	.7500	.8660	.6667	.8877	FS	1.272	1.104	.6364	.6742
Lapses	2.583	2.353	3.917	2.539	Lapses	2.091	1.300	5.909	6.332
Day 2					Day 2				
μ	.2587	.0278	.3024	.0287	μ	.2988	.0279	.2899	.0182
τ	.0536	.0248	.0662	.0267	τ	.0879	.0560	.1245	.1001
σ	.0208	.0088	.0269	.0101	σ	.0235	.0104	.0265	.0120
FS	1.167	1.267	.9167	.9962	FS	1.182	1.888	1.636	1.859
Lapses	2.750	2.598	5.000	4.612	Lapses	10.72	11.12	14.36	13.48

Appendix B

Table B1. Separate repeated measures ANOVA on alpha frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated (p<0.05).

Variable	df	MS	F	Partial η^2
Alpha Frontal				
Between subject				
Condition[a]	1, 17	.112	.143	.008
Within subject				
Day[b]	1, 17	.345	2.549	.130
Block[c]	2, 34	.076	1.408	.076
Day * Condition	1, 17	1.679	.00	.00
Block * Condition	2, 34	.076	1.414	.077
Day* Block	2, 34	.028	.777	.044
Day* Block*Condition	2, 34	.063	1.772	.094
Alpha Central				
Between subject				
Condition[a]	1, 17	1.216	1.594	.086
Within subject				
Day[b]	1, 17	1.222	6.504*	.277
Block[c]	2, 34	.457	.295	.017
Day * Condition	1, 17	.016	.085	.005
Block * Condition	2, 34	1.266	.816	.046
Day* Block	2, 34	.230	1.802	.096
Day* Block*Condition	2, 34	.016	.127	.007
Alpha Parietal				
Between subject				
Condition[a]	1, 17	0.001	.001	.000
Within subject				
Day[b]	1, 17	2.339	15.113**	.471
Block[c]	2, 34	.373	3.616	.175
Day * Condition	1, 17	.620	4.006	.191
Block * Condition	2, 34	.143	1.387	.075
Day* Block	2, 34	.042	.924	.052
Day* Block*Condition	2, 34	.064	1.408	.076
Alpha Occipital				
Between subject				
Condition[a]	1, 17	.035	.024	.001

(continued)

Table B1. (continued)

Variable	df	MS	F	Partial η^2
Within subject				
Day[b]	1, 17	3.160	18.398**	.520
Block[c]	2, 34	.515	6.02*	.262
Day * Condition	1, 17	.694	4.04	.192
Block * Condition	2, 34	.070	.815	.046
Day* Block	2, 34	.045	2.822	.142
Day* Block*Condition	2, 34	.210	6.627**	.280

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table B2. Separate repeated measures ANOVA on alpha frequencies (absolute) for each block at occipital sites during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha block 1				
Between subject				
Condition[a]	1, 17	.011	.016	.001
Within subject				
Day[b]	1, 17	1.239	16.538**	.493
Day * Condition	1, 17	.662	8.838**	.342
Alpha block 2				
Between subject				
Condition[a]	1, 17	.108	.215	.013
Within subject				
Day[b]	1, 17	1.395	16.158	.487
Day * Condition	1, 17	.215	2.492	.128
Alpha block 3				
Between subject				
Condition[a]	1, 17	.010	.023	.001
Within subject				
Day[b]	1, 17	.616	14.570**	.462
Day * Condition	1, 17	.027	.647	.037

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

Table B3. Paired-sample t-test on alpha frequencies (absolute) comparing eyes closed for sleep deprived and full sleep participants at occipital sites on day 1 and day 2.

Variable	df	Mean	Std. Deviation	t-val.
Sleep Deprivation				
Occipital				
Day 1 * Day 2	8	.626	.353	5.313**
Sleep				
Occipital				
Day 1 * Day 2	9	.097	.415	.742

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

Table B4. Separate repeated measures ANOVA on alpha frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha Frontal				
Between subject				
Condition[a]	1, 17	.521	.857	.048
Within subject				
Day[b]	1, 17	.083	.705	.04
Block[c]	2, 34	.061	.733	.041
Day * Condition	1, 17	.052	.439	.025
Block * Condition	2, 34	.064	.767	.043
Day* Block	2, 34	.0121	2.093	.110
Day* Block*Condition	2, 34	.069	1.195	.066
Alpha Central				
Between subject				
Condition[a]	1, 17	3.573	4.546*	.211
Within subject				
Day[b]	1, 17	.385	2.353	.122
Block[c]	2, 34	.338	.214	.012
Day * Condition	1, 17	8.946	.001.	.00
Block * Condition	2, 34	1.201	.761	.043
Day* Block	2, 34	.318	2.137	.112
Day* Block*Condition	2, 34	.061	.410	.024
Alpha Parietal				
Between subject				
Condition[a]	1, 17	2.363	2.115	.111
Within subject				
Day[b]	1, 17	.679	8.203*	.325
Block[c]	2, 34	.250	3.514	.171
Day * Condition	1, 17	.271	3.277	.162
Block * Condition	2, 34	.075	1.058	.059
Day* Block	2, 34	.051	.638	.036
Day* Block*Condition	2, 34	.014	.178	.010
Alpha Occipital				
Between subject				
Condition[a]	1, 17	.035	.024	.001
Within subject				

(continued)

Table B4. (continued)

Variable	df	MS	F	Partial η^2
Day[b]	1, 17	.905	14.5**	.460
Block[c]	2, 34	.357	5.817*	.255
Day * Condition	1, 17	.248	3.969	.189
Block * Condition	2, 34	.061	.987	.055
Day* Block	2, 34	.093	1.952	.103
Day* Block*Condition	2, 34	.104	2.182	.114

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

Table B5. Descriptive alpha frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.546	.3706	5.649	.3854	5.719	.2536
Central	5.458	.9657	5.517	.5442	5.025	1.210
Parietal	5.780	.6138	5.929	.5116	5.983	.4103
Occipital	6.149	.6605	6.323	.5893	6.415	.5027
Day 2						
Frontal	5.462	.3819	5.559	.4414	5.565	.3827
Central	5.157	.4155	5.328	.4371	4.965	1.057
Parietal	5.668	.7081	5.771	.5573	5.835	.5426
Occipital	6.052	.7126	6.090	.7013	6.213	.6195
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.779	.6748	5.637	.4715	5.688	.3659
Central	5.622	.7222	5.486	.5060	5.583	.4890
Parietal	6.090	.6623	5.976	.4845	6.084	.4338
Occipital	6.447	.6145	6.367	.4597	6.436	.4223
Day 2						
Frontal	5.534	.4056	5.579	.4018	5.658	.4173
Central	5.236	.3875	5.325	.3666	5.438	.3712
Parietal	5.542	.3448	5.509	.3511	5.795	.3146
Occipital	5.821	.3713	5.833	.3088	6.127	.2984

Table B6. Descriptive alpha frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.437	.4140	5.478	.3429	5.579	.2624
Central	5.240	.9474	5.231	.4562	4.873	1.263
Parietal	5.373	.5617	5.447	.5212	5.527	.4658
Occipital	5.695	.5658	5.822	.5404	5.915	.4864
Day 2						
Frontal	5.320	.2717	5.426	.2976	5.458	.2654
Central	4.979	.3883	5.125	.3298	4.795	1.094
Parietal	5.285	.5956	5.383	.4567	5.510	.4611
Occipital	5.625	.6240	5.699	.5136	5.853	.6046
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.691	.7063	5.518	.4931	5.564	.3468
Central	5.494	.8037	5.323	.4407	5.495	.4549
Parietal	5.887	.6682	5.741	.4906	5.878	.3730
Occipital	6.181	.6393	6.034	.4396	6.113	.3651
Day 2						
Frontal	5.494	.3276	5.626	.4136	5.619	.4183
Central	5.193	.3675	5.362	.3941	5.414	.4177
Parietal	5.529	.3214	5.533	.4122	5.687	.4041
Occipital	5.711	.3549	5.816	.3772	5.984	.3645

Appendix C

Table C1. Separate repeated measures ANOVA on beta frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Beta Frontal				
Between subject				
Condition[a]	1, 17	.022	.071	.004
Within subject				
Day[b]	1, 17	.012	.123	.007
Block[c]	2, 34	.052	.584	.033
Day * Condition	1, 17	.046	.482	.028
Block * Condition	2, 34	.149	1.681	.090
Day* Block	2, 34	.179	2.726	.138
Day* Block*Condition	2, 34	.110	1.672	.090
Beta Central				
Between subject				
Condition[a]	1, 17	.384	.365	.049
Within subject				
Day[b]	1, 17	.015	.143	.008
Block[c]	2, 34	.549	.395	.023
Day * Condition	1, 17	.011	.105	.006
Block * Condition	2, 34	1.032	.742	.042
Day* Block	2, 34	.224	1.936	.102
Day* Block*Condition	2, 34	.039	.340	.020
Beta Parietal				
Between subject				
Condition[a]	1, 17	.023	.103	.006
Within subject				
Day[b]	1, 17	.122	1.071	.059
Block[c]	2, 34	.169	1.504	.081
Day * Condition	1, 17	.094	.823	.046
Block * Condition	2, 34	.123	1.089	.060
Day* Block	2, 34	.112	1.811	.096
Day* Block*Condition	2, 34	.089	1.439	.078
Beta Occipital				
Between subject				
Condition[a]	1, 17	.022	.069	.004

(continued)

Table C1. (continued)

Variable	df	MS	F	Partial η^2
Within subject				
Day[b]	1, 17	.327	3.596	.175
Block[c]	2, 34	.125	1.806	.096
Day * Condition	1, 17	.074	.814	.046
Block * Condition	2, 34	.053	.761	.043
Day* Block	2, 34	.126	2.440	.126
Day* Block*Condition	2, 34	.114	2.199	.115

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table C2. Separate repeated measures ANOVA on beta frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Beta Frontal				
Between subject				
Condition[a]	1, 17	678.07	629.5***	.974
Within subject				
Day[b]	1, 17	.044	.121	.007
Block[c]	2, 34	.500	1.515	.082
Day * Condition	1, 17	.210	.581	.033
Block * Condition	2, 34	.781	2.369	.122
Day* Block	2, 34	.570	3.698*	.179
Day* Block*Condition	2, 34	.030	.195	.011
Beta Central				
Between subject				
Condition[a]	1, 17	.384	.365	.049
Within subject				
Day[b]	1, 17	.015	.143	.008
Block[c]	2, 34	.549	.395	.023
Day * Condition	1, 17	.011	.105	.006
Block * Condition	2, 34	1.032	.742	.042
Day* Block	2, 34	.224	1.936	.102
Day* Block*Condition	2, 34	.039	.340	.020
Beta Parietal				
Between subject				
Condition[a]	1, 17	.088	.282	.016
Within subject				
Day[b]	1, 17	.098	.789	.044
Block[c]	2, 34	.153	.907	.051
Day * Condition	1, 17	.043	.345	.020
Block * Condition	2, 34	.103	.608	.035
Day* Block	2, 34	.223	2.008	.106
Day* Block*Condition	2, 34	.050	.451	.026
Beta Occipital				
Between subject				
Condition[a]	1, 17	.024	.069	.004
Within subject				

(continued)

Table C2. (continued)

Variable	df	MS	F	Partial η^2
Day[b]	1, 17	.223	2.114	.111
Day* Block	2, 34	.276	2.644	.135
Day* Block*Condition	2, 34	.112	1.069	.059

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table C3. Descriptive beta frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	4.675	.2986	4.748	.3811	4.822	.2846
Central	4.511	.5222	4.576	.4247	4.115	1.378
Parietal	4.578	.2423	4.668	.3071	4.733	.2656
Occipital	4.965	.3074	5.032	.2734	5.118	.2793
Day 2						
Frontal	4.618	.2552	4.816	.2690	4.750	.1314
Central	4.411	.4298	4.593	.4470	4.188	1.001
Parietal	4.549	.3241	4.701	.2535	4.704	.2400
Occipital	4.912	.2380	4.953	.2342	5.081	.3360
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	4.820	.6790	4.579	.3036	4.640	.2674
Central	4.647	.7194	4.437	.3657	4.527	.3322
Parietal	4.852	.6445	4.648	.2751	4.735	.3090
Occipital	5.228	.6154	5.066	.3010	5.058	.2802
Day 2						
Frontal	4.663	.2810	4.734	.2807	4.825	.3019
Central	4.386	.3164	4.540	.3164	4.575	.2858
Parietal	4.522	.2475	4.590	.2300	4.755	.2480
Occipital	4.857	.2802	4.937	.2028	5.083	.2665

Table C4. Descriptive beta frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	9.525	1.038	9.584	.8100	9.737	.6588
Central	4.570	.7225	4.530	.2077	4.054	1.449
Parietal	4.583	.4714	4.587	.3154	4.642	.2814
Occipital	4.940	.3664	4.933	.2625	5.036	.2951
Day 2						
Frontal	9.244	.5773	9.599	.5605	9.862	.4420
Central	4.368	.4780	4.570	.3639	4.290	1.126
Parietal	4.478	.3865	4.563	.2467	4.713	.3208
Occipital	4.831	.2925	4.865	.2023	5.048	.4062
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	4.822	.7612	4.525	.3500	4.587	.3200
Central	4.623	.8331	4.331	.3868	4.482	.3660
Parietal	4.841	.7362	4.572	.2983	4.683	.3351
Occipital	5.188	.7255	4.957	.3483	4.952	.3472
Day 2						
Frontal	4.670	.3005	4.829	.3250	4.811	.3422
Central	4.349	.3431	4.524	.3744	4.497	.3462
Parietal	4.529	.2325	4.591	.2688	4.683	.3005
Occipital	4.797	.3001	4.917	.2392	5.016	.3374

Appendix D

Table D1. Separate repeated measures ANOVA on theta frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Theta Frontal				
Between subject				
Condition[a]	1, 17	.258	.561	.032
Within subject				
Day[b]	1, 17	.243	3.889	.186
Block[c]	2, 34	.170	4.180*	.197
Day * Condition	1, 17	.579	9.258**	.353
Block * Condition	2, 34	.049	1.193	.066
Day* Block	2, 34	.066	2.062	.108
Day* Block*Condition	2, 34	.042	1.309	.071
Theta Central				
Between subject				
Condition[a]	1, 17	.244	.614	.035
Within subject				
Day[b]	1, 17	.010	.040	.002
Block[c]	2, 34	.267	.174	.010
Day * Condition	1, 17	.616	2.570	.131
Block * Condition	2, 34	.810	.528	.030
Day* Block	2, 34	.154	.969	.054
Day* Block*Condition	2, 34	.045	.287	.017
Theta Parietal				
Between subject				
Condition[a]	1, 17	.333	.506	.029
Within subject				
Day[b]	1, 17	.084	.646	.037
Block[c]	2, 34	.844	7.513**	.306
Day * Condition	1, 17	.026	.198	.011
Block * Condition	2, 34	.190	1.689	.090
Day* Block	2, 34	.038	.526	.030
Day* Block*Condition	2, 34	.020	.269	.016
Theta Occipital				
Between subject				

(continued)

Table D1. (continued)

Variable	df	MS	F	Partial η^2
Condition[a]	1, 17	.303	.374	.022
Within subject				
Day[b]	1, 17	.011	.123	.007
Block[c]	2, 34	.587	10.044**	.371
Day * Condition	1, 17	.152	1.750	.093
Block * Condition	2, 34	.061	1.039	.058
Day* Block	2, 34	.052	1.863	.099
Day* Block*Condition	2, 34	.060	2.124	.111

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table D2. Separate repeated measures ANOVA on theta frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated (p<0.05).

Variable	df	MS	F	Partial η^2
Theta Frontal				
Between subject				
Condition[a]	1, 17	.060	.190	.011
Within subject				
Day[b]	1, 17	.103	1.341	.073
Block[c]	2, 34	.113	1.040	.058
Day * Condition	1, 17	.644	8.385*	.330
Block * Condition	2, 34	.083	.757	.043
Day* Block	2, 34	.191	3.607	.175
Day* Block*Condition	2, 34	.051	.955	.053
Theta Central				
Between subject				
Condition[a]	1, 17	.129	.407	.023
Within subject				
Day[b]	1, 17	.006	.026	.002
Block[c]	2, 34	.534	.364	.021
Day * Condition	1, 17	.614	2.701	.137
Block * Condition	2, 34	.977	.668	.038
Day* Block	2, 34	.377	1.957	.103
Day* Block*Condition	2, 34	.061	.317	.018
Theta Parietal				
Between subject				
Condition[a]	1, 17	.334	.535	.031
Within subject				
Day[b]	1, 17	.009	.098	.006
Block[c]	2, 34	.285	2.559	.131
Day * Condition	1, 17	.019	.216	.013
Block * Condition	2, 34	.230	2.066	.108
Day* Block	2, 34	.105	.947	.053
Day* Block*Condition	2, 34	.004	.037	.002
Theta Occipital				
Between subject				
Condition[a]	1, 17	.286	.442	.025
Within subject				

(continued)

Table D2. (continued)

Variable	df	MS	F	Partial η^2
Day[b]	1, 17	.001	.013	.001
Block[c]	2, 34	.370	3.895	.186
Day * Condition	1, 17	.147	1.719	.092
Block * Condition	2, 34	.101	1.064	.059
Day* Block	2, 34	.220	3.353	.165
Day* Block*Condition	2, 34	.070	1.068	.059

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table D3. Descriptive theta frequencies (absolute) for each site during eye closed and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.586	.2752	5.679	.4338	5.804	.3730
Central	5.505	1.128	5.567	.7994	5.173	1.014
Parietal	5.477	.4328	5.642	.5039	5.801	.4363
Occipital	5.771	.4222	5.957	.5733	6.108	.2387
Day 2						
Frontal	5.545	.2663	5.658	.3084	5.715	.2279
Central	5.259	.4622	5.445	.4207	5.154	.9570
Parietal	5.478	.6351	5.713	.4689	5.802	.3901
Occipital	5.728	.6183	5.925	.5444	6.021	.4225
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.680	.5191	5.549	.2921	5.697	.2549
Central	5.385	.5998	5.273	.3385	5.423	.3013
Parietal	5.725	.5539	5.629	.2949	5.801	.2583
Occipital	5.980	.4840	5.917	.2550	6.029	.3109
Day 2						
Frontal	5.799	.2729	5.923	.2755	5.910	.3340
Central	5.427	.2926	5.563	.2523	5.587	.3206
Parietal	5.710	.3629	5.759	.1522	5.943	.2139
Occipital	5.900	.2341	6.120	.1665	6.194	.2939

Table D4. Descriptive theta frequencies (absolute) for each site during eye open and comparing sleep deprived and full sleep participants.

Sleep condition						
	Block					
	1		2		3	
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.692	.3397	5.708	.4126	5.839	.3318
Central	5.548	1.209	5.548	.6766	5.076	.9996
Parietal	5.476	.4509	5.587	.4557	5.659	.4251
Occipital	5.748	.4456	5.834	.3815	5.936	.3610
Day 2						
Frontal	5.547	.2441	5.689	.2374	5.733	.2470
Central	5.198	.4388	5.430	.3957	5.061	.9167
Parietal	5.369	.5546	5.622	.4543	5.706	.4589
Occipital	5.603	.5737	5.782	.4755	5.900	.5062
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	5.740	.5564	5.545	.3345	5.640	.2405
Central	5.380	.6530	5.209	.3410	5.345	.2731
Parietal	5.719	.5745	5.558	.3254	5.692	.3007
Occipital	5.953	.5556	5.793	.2610	5.858	.2779
Day 2						
Frontal	5.753	.1576	5.926	.2527	5.879	.3233
Central	5.328	.2476	5.514	.2592	5.491	.3203
Parietal	5.655	.3306	5.684	.1691	5.761	.2638
Occipital	5.781	.2250	5.989	.1516	6.032	.2471

Appendix E

Table E1. Separate repeated measures ANOVA on ratio frequencies for alpha:beta at each site during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha:beta Frontal				
Between subject				
Condition[a]	1, 17	.010	.292	.017
Within subject				
Day[b]	1, 17	.026	6.892	.288
Block[c]	2, 34	4.565	.002	.000
Day * Condition	1, 17	.033	.784	.044
Block * Condition	2, 34	.002	.582	.033
Day* Block	2, 34	.004	3.094	.024
Day* Block*Condition	2, 34	.001	.410	.024
Alpha:beta Central				
Between subject				
Condition[a]	1, 17	.180	.468	.027
Within subject				
Day[b]	1, 17	.468	1.46	.079
Block[c]	2, 34	.569	.919	.051
Day * Condition	1, 17	.214	.669	.038
Block * Condition	2, 34	.531	.857	.048
Day* Block	2, 34	.428	.907	.051
Day* Block*Condition	2, 34	.412	.872	.049
Alpha:beta Parietal				
Between subject				
Condition[a]	1, 17	.274	9.833	.366
Within subject				
Day[b]	1, 17	.095	17.49 **	.507
Block[c]	2, 34	.000	.087	.005
Day * Condition	1, 17	.403	73.98 ***	.813
Block * Condition	2, 34	.001	.222	.013
Day* Block	2, 34	.003	2.233	.116
Day* Block*Condition	2, 34	.001	.847	.047
Alpha:beta Occipital				

(continued)

Table E1. (continued)

Variable	df	MS	F	Partial η^2
Between subject				
Condition[a]	1, 17	.004	.118	.007
Within subject				
Day[b]	1, 17	.049	9.5**	.359
Block[c]	2, 34	.002	1.001	.056
Day * Condition	1, 17	.010	1.864	.099
Block * Condition	2, 34	.002	.718	.041
Day* Block	2, 34	.003	1.847	.098
Day* Block*Condition	2, 34	.000	.105	.006

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table E2. Separate repeated measures ANOVA on ratio frequencies for alpha:beta at each site during eye open and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated (p<0.05).

Variable	df	MS	F	Partial η^2
Alpha:beta Frontal				
Between subject				
Condition[a]	1, 17	.055	1.731	.092
Within subject				
Day[b]	1, 17	.017	6.345*	.272
Block[c]	2, 34	.000	.147	.009
Day * Condition	1, 17	.004	1.350	.074
Block * Condition	2, 34	.001	.309	.018
Day* Block	2, 34	.006	5.604	.248
Day* Block*Condition	2, 34	6.746	.058	.003
Alpha:beta Central				
Between subject				
Condition[a]	1, 17	12.842	1.121	.062
Within subject				
Day[b]	1, 17	9.989	.849	.048
Block[c]	2, 34	19.441	.890	.050
Day * Condition	1, 17	10.708	.910	.051
Block * Condition	2, 34	20.086	.920	.051
Day* Block	2, 34	20.030	.873	.049
Day* Block*Condition	2, 34	20.076	.875	.049
Alpha:beta Parietal				
Between subject				
Condition[a]	1, 17	.601	22.97***	.575
Within subject				
Day[b]	1, 17	.176	23.32***	.578
Block[c]	2, 34	.001	.380	.011
Day * Condition	1, 17	.324	45.29***	.727
Block * Condition	2, 34	.001	.380	.022
Day* Block	2, 34	.003	2.246	.117
Day* Block*Condition	2, 34	.002	1.170	.064
Alpha:beta Occipital				
Between subject				

(continued)

Table E2. (continued)

Variable	df	MS	F	Partial η^2
Condition[a]	1, 17	.037	1.186	.065
Within subject				
Day[b]	1, 17	.008	2.272	.118
Block[c]	2, 34	.003	1.778	.095
Day * Condition	1, 17	.003	.823	.046
Block * Condition	2, 34	.001	.850	.048
Day* Block	2, 34	.002	2.186	.114
Day* Block*Condition	2, 34	7.94	.071	.004

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table E3. Descriptive ratio frequencies for alpha:beta at each site during eye closed and comparing sleep deprived and full sleep participants.

Sleep condition						
	Block					
	1		2		3	
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	1.190	.0937	1.195	.1048	1.190	.0889
Central	1.206	.1015	1.206	.0785	1.778	1.860
Parietal	1.063	.1108	1.063	.0745	1.053	.0871
Occipital	1.238	.1042	1.257	.1060	1.256	.1024
Day 2						
Frontal	1.186	.1061	1.156	.0960	1.172	.0861
Central	1.174	.0885	1.163	.0761	1.207	.1142
Parietal	1.243	.1078	1.227	.0959	1.240	.0897
Occipital	1.230	.1210	1.227	.1055	1.224	.1075
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	1.203	.0770	1.232	.0854	1.228	.0814
Central	1.216	.0927	1.239	.0972	1.235	.0949
Parietal	1.260	.0779	1.286	.0771	1.286	.0662
Occipital	1.237	.0765	1.258	.0722	1.274	.0632
Day 2						
Frontal	1.187	.0598	1.180	.0755	1.174	.0816
Central	1.195	.0631	1.180	.0783	1.191	.0816
Parietal	1.226	.0539	1.201	.0669	1.220	.0645
Occipital	1.199	.0586	1.182	.0515	1.208	.0721

Table E4. Descriptive ratio frequencies for alpha:beta at each site during eye open and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	1.142	.0918	1.157	.0927	1.157	.0878
Central	1.149	.1090	1.156	.0817	-2.508	11.56
Parietal	.9904	.1209	.9927	.0926	.9951	.0917
Occipital	1.154	.0978	1.182	.1076	1.177	.1049
Day 2						
Frontal	1.152	.0909	1.129	.0791	1.136	.0715
Central	1.145	.0751	1.124	.0559	1.148	1.333
Parietal	1.180	.0882	1.179	.0708	1.169	.0583
Occipital	1.162	.0855	1.171	.0879	1.160	.0795
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	1.186	.0755	1.220	.0765	1.215	.0687
Central	1.196	.0877	1.230	.0897	1.229	.0901
Parietal	1.222	.0755	1.256	.0682	1.257	.0602
Occipital	1.197	.0712	1.218	.0599	1.236	.0527
Day 2						
Frontal	1.179	.0680	1.167	.0782	1.170	.0843
Central	1.197	.0723	1.189	.0947	1.206	.0843
Parietal	1.222	.0543	1.207	.0866	1.216	.0733
Occipital	1.192	.0531	1.184	.0688	1.196	.0752

Appendix F

Table F1 Separate repeated measures ANOVA on ratio frequencies for alpha:theta at each site during eye closed and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha:theta Frontal				
Between subject				
Condition[a]	1, 17	.001	.087	.005
Within subject				
Day[b]	1, 17	.036	18.58***	.522
Block[c]	2, 34	.001	.702	.040
Day * Condition	1, 17	.016	8.268*	.327
Block * Condition	2, 34	.000	.211	.012
Day* Block	2, 34	.001	2.960	.148
Day* Block*Condition	2, 34	.001	2.932	.147
Alpha:theta Central				
Between subject				
Condition[a]	1, 17	.015	.749	.042
Within subject				
Day[b]	1, 17	.049	24.14***	.587
Block[c]	2, 34	.004	1.727	.092
Day * Condition	1, 17	.027	13.368**	.440
Block * Condition	2, 34	.004	1.727	.096
Day* Block	2, 34	.001	3.494*	.170
Day* Block*Condition	2, 34	7.448	.193	.011
Alpha:theta Parietal				
Between subject				
Condition[a]	1, 17	.012	.462	.026
Within subject				
Day[b]	1, 17	.100	67.88***	.800
Block[c]	2, 34	.003	1.741	.093
Day * Condition	1, 17	.026	17.371**	.505
Block * Condition	2, 34	.001	.655	.037
Day* Block	2, 34	.002	4.543*	.211
Day* Block*Condition	2, 34	.000	1.301	.071
Alpha:theta Occipital				
Between subject				
Condition[a]	1, 17	.019	.702	.040

(continued)

Table F1. (continued)

Variable	df	MS	F	Partial η^2
Within subject				
Day[b]	1, 17	.096	30.96***	.646
Block[c]	2, 34	.003	1.556	.084
Day * Condition	1, 17	.042	13.39**	.441
Block * Condition	2, 34	.001	.614	.035
Day* Block	2, 34	.003	6.939**	.290
Day* Block*Condition	2, 34	.001	1.478	.080

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table F2. Separate repeated measures ANOVA on ratio frequencies for alpha:theta at each site during eye open and comparing sleep deprived and full sleep participants. Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha:theta Frontal				
Between subject				
Condition[a]	1, 17	.006	.633	.036
Within subject				
Day[b]	1, 17	.011	7.897*	.317
Block[c]	2, 34	5.163	.086	.005
Day * Condition	1, 17	.009	6.314*	.271
Block * Condition	2, 34	1.557	.024	.001
Day* Block	2, 34	.000	1.113	.061
Day* Block*Condition	2, 34	.000	.374	.022
Alpha:theta Central				
Between subject				
Condition[a]	1, 17	.093	4.849*	.222
Within subject				
Day[b]	1, 17	.010	6.071*	.263
Block[c]	2, 34	.001	.222	.013
Day * Condition	1, 17	.019	11.485**	.403
Block * Condition	2, 34	.006	1.136	.063
Day* Block	2, 34	.000	.934	.052
Day* Block*Condition	2, 34	5.168	.152	.009
Alpha:theta Parietal				
Between subject				
Condition[a]	1, 17	.028	2.072	.109
Within subject				
Day[b]	1, 17	.025	40.01***	.702
Block[c]	2, 34	.001	1.562	.084
Day * Condition	1, 17	.014	21.27***	.556
Block * Condition	2, 34	.001	1.596	.086
Day* Block	2, 34	.000	1.720	.092
Day* Block*Condition	2, 34	.000	.640	.036
Alpha:theta Occipital				
Between subject				
Condition[a]	1, 17	.009	.869	.049
Within subject				

(continued)

Table F2. (continued)

Variable	df	MS	F	Partial η^2
Day[b]	1, 17	.024	27.79***	.620
Block[c]	2, 34	.001	.833	.047
Day * Condition	1, 17	.023	26.69***	.611
Block * Condition	2, 34	.000	.346	.020
Day* Block	2, 34	.000	4.873	.223
Day* Block*Condition	2, 34	.000	.787	.044

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks.

Table F3. Descriptive ratio frequencies for alpha:theta at each site during eye closed and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	.9943	.0737	.9975	.0707	.9881	.0639
Central	.9964	.0701	.9973	.0703	.9571	.1109
Parietal	1.056	.0840	1.054	.0817	1.035	.0863
Occipital	1.065	.0833	1.065	.0830	1.053	.0900
Day 2						
Frontal	.9865	.0753	.9831	.0684	.9748	.0718
Central	.9829	.0637	.9794	.0577	.9568	.0799
Parietal	1.036	.0915	1.012	.0891	1.008	.0954
Occipital	1.059	.0997	1.029	.0976	1.034	.1065
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	1.016	.0425	1.015	.0573	.9984	.0470
Central	1.043	.0414	1.040	.0650	1.029	.0650
Parietal	1.063	.0405	1.061	.0533	1.048	.0473
Occipital	1.077	.0410	1.076	.0521	1.068	.0490
Day 2						
Frontal	.9535	.0352	.9411	.0296	.9571	.0360
Central	.9645	.0453	.9568	.0395	.9737	.0405
Parietal	.9727	.0548	.9561	.0447	.9753	.0440
Occipital	.9862	.0410	.9530	.0396	.9918	.0468

Table F4. Descriptive ratio frequencies for alpha:theta at each site during eye open and comparing sleep deprived and full sleep participants.

	Block					
	1		2		3	
Sleep condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	.9555	.0500	.9615	.0523	.9567	.0457
Central	.9502	.0526	.9468	.0567	.9206	.1373
Parietal	.9812	.0651	.9747	.0491	.9776	.0592
Occipital	.9902	.0544	.9969	.0466	.9965	.0581
Day 2						
Frontal	.9601	.0534	.9544	.0487	.9530	.0493
Central	.9593	.0430	.9450	.0397	.9346	.0938
Parietal	.9849	.0623	.9580	.0437	.9664	.0513
Occipital	1.004	.0570	.9860	.0475	.9915	.0503
Sleep deprivation condition						
Day 1	Mean	SD	Mean	SD	Mean	SD
Frontal	.9895	.0477	.9944	.0529	.9862	.0376
Central	1.019	.0513	1.021	.0674	1.028	.0598
Parietal	1.029	.0411	1.032	.0531	1.033	.0378
Occipital	1.038	.0399	1.041	.0479	1.043	.0343
Day 2						
Frontal	.9544	.0363	.9483	.0348	.9551	.0295
Central	.9745	.0480	.9721	.0481	.9858	.0463
Parietal	.9790	.0509	.9727	.0520	.9867	.0416
Occipital	.9876	.0358	.9703	.0404	.9918	.0352

Appendix G

Table G1. Separate repeated measures ANOVA on ratio frequencies for alpha:theta at each site during eye closed and comparing sleep deprived and full sleep participants (Including missing participants). Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha:theta Frontal				
Between subject				
Condition[a]	1, 21	.012	1.127	.051
Within subject				
Day[b]	1, 21	.029	21.06***	.501
Block[c]	1, 21	.000	1.042	.047
Day * Condition	1, 21	.012	8.730*	.294
Block * Condition	1, 21	.001	1.476	.066
Day* Block	1, 21	.000	1.34	.06
Day* Block*Condition	1, 21	.002	6.123*	.226
Alpha:theta Central				
Between subject				
Condition[a]	1, 21	.003	.646	.010
Within subject				
Day[b]	1, 21	.032	20.04***	.488
Block[c]	1, 21	.001	.570	.026
Day * Condition	1, 21	.021	13.340**	.388
Block * Condition	1, 21	.003	1.391	.062
Day* Block	1, 21	.004	6.796*	.245
Day* Block*Condition	1, 21	.000	.431	.020
Alpha:theta Parietal				
Between subject				
Condition[a]	1, 21	.016	.946	.043
Within subject				
Day[b]	1, 21	.083	66.72***	.761
Block[c]	1, 21	6.147	.088	.004
Day * Condition	1, 21	.015	11.97**	.363
Block * Condition	1, 21	.001	2.066	.090
Day* Block	1, 21	.001	.2.178	.094
Day* Block*Condition	1, 21	2.192	.001	.00
Alpha:theta Occipital				
Between subject				
Condition[a]	1, 21	.024	1.462	.065

(continued)

Table G1. (continued)

Variable	df	MS	F	Partial η^2
Within subject				
Day[b]	1, 21	.094	45.14***	.682
Block[c]	1, 21	1.871	.186	.082
Day * Condition	1, 21	.033	15.93**	.431
Block * Condition	1, 21	.001	1.931	.084
Day* Block	1, 21	.002	6.044*	.223
Day* Block*Condition	1, 21	.001	2.017	.088

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks, however block 1 was excluded.

Table G2. Separate repeated measures ANOVA on ratio frequencies for alpha:theta for each during eye closed and comparing sleep deprived and full sleep participants (Including missing participants). Huynh-Feldt corrections were used because the sphericity assumption was violated ($p<0.05$).

Variable	df	MS	F	Partial η^2
Alpha:theta Frontal (Block 2)				
Between subject				
Condition	1, 21	.009	1.566	.069
Within subject				
Day	1, 21	.018	18.47***	.468
Day*Condition	1, 21	.011	11.587**	.356
Alpha:theta Frontal (Block 3)				
Between subject				
Condition	1, 21	.004	.699	.032
Within subject				
Day	1, 21	.012	17.09***	.449
Day*Condition	1, 21	.002	3.599	.149

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks, however block 1 was excluded.

Table G3. Paired-sample t-test on alpha:theta (including all participants) comparing eyes closed for sleep deprived and full sleep participants at frontal sites on day 1 and day 2.

Variable	df	Mean	Std. Deviation	t-val.
Sleep Deprivation				
Frontal				
Day 1 * Day 2	10	.0713	.047	5.082**
Sleep				
Frontal				
Day 1 * Day 2	11	.0083	.0423	.678

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

Table G4. Separate repeated measures ANOVA on ratio frequencies for alpha:theta at each site during open and comparing sleep deprived and full sleep participants (Including missing participants). Huynh-Feldt corrections were used because the sphericity assumption was violated (p<0.05).

Variable	df	MS	F	Partial η^2
Alpha:theta Frontal				
Between subject				
Condition[a]	1, 21	.001	.195	.009
Within subject				
Day[b]	1, 21	.014	13.863**	.398
Block[c]	1, 21	.001	1.127	.051
Day * Condition	1, 21	.003	3.208	.133
Block * Condition	1, 21	.000	.688	.032
Day* Block	1, 21	.001	3.519	.144
Day* Block*Condition	1, 21	2.469	.009	.000
Alpha:theta Central				
Between subject				
Condition[a]	1, 21	.055	2.997	.125
Within subject				
Day[b]	1, 21	.006	4.675*	.182
Block[c]	1, 21	3.328	.009	.000
Day * Condition	1, 21	.013	10.863**	.341
Block * Condition	1, 21	.002	.651	.030
Day* Block	1, 21	.003	4.023	.161
Day* Block*Condition	1, 21	.002	2.618	.111
Alpha:theta Parietal				
Between subject				
Condition[a]	1, 21	.022	2.298	.099
Within subject				
Day[b]	1, 21	.022	17.66***	.457
Block[c]	1, 21	.001	1.707	.075
Day * Condition	1, 21	.003	2.226	.096
Block * Condition	1, 21	.000	.756	.035
Day* Block	1, 21	.001	1.472	.066
Day* Block*Condition	1, 21	.000	.723	.033
Alpha:theta Occipital				
Between subject				
Condition[a]	1, 21	.001	.140	.007
Within subject				

(continued)

Table G4. (continued)

Variable	df	MS	F	Partial η^2
Day[b]	1, 21	.037	41.61***	.665
Block[c]	1, 21	.001	.912	.042
Day * Condition	1, 21	.018	20.22***	.491
Block * Condition	1, 21	.000	.421	.020
Day* Block	1, 21	.002	4.221	.167
Day* Block*Condition	1, 21	3.174	.006	.000

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

a. There are two conditions: Sleep deprivation or full sleep

b. There are two days of recorded data, the day before condition (Sleep deprivation or full sleep) and the day following condition.

c. For day 1 and 2 the tasks are presented three times resulting in three blocks, however block 1 was excluded.

Table G5. Descriptive ratio frequencies for alpha:theta at each site during closed and comparing sleep deprived and full sleep participants (Including missing participants).

	Block			
	1		2	
Sleep condition				
Day 1	Mean	SD	Mean	SD
Frontal	1.003	.0657	.9990	.0646
Central	1.006	.0667	.9704	.1059
Parietal	1.056	.0742	1.044	.0811
Occipital	1.065	.0752	1.060	.0833
Day 2				
Frontal	.9949	.0677	.9817	.0694
Central	.9829	.0541	.9795	.0937
Parietal	1.016	.0839	1.016	.0894
Occipital	1.034	.0899	1.038	.0977
Sleep Deprivation condition				
Day 1	Mean	SD	Mean	SD
Frontal	1.007	.0553	.9954	.0430
Central	1.033	.0586	1.028	.0585
Parietal	1.048	.0602	1.051	.0428
Occipital	1.068	.0515	1.067	.0439
Day 2				
Frontal	.9357	.0315	.9488	.0391
Central	.9559	.0469	.9697	.0525
Parietal	.9560	.0486	.9717	.0488
Occipital	.9499	.0395	.9816	.0512

Table G6. Descriptive ratio frequencies for alpha:theta at each site during open and comparing sleep deprived and full sleep participants (Including missing participants).

	Block			
	1		2	
Sleep condition				
Day 1	Mean	SD	Mean	SD
Frontal	.9734	.0593	.9576	.0564
Central	.9645	.0675	.9334	.1307
Parietal	.9935	.0655	.9849	.0690
Occipital	1.011	.0649	1.002	.0649
Day 2				
Frontal	.9543	.0475	.9506	.0544
Central	.9532	.0408	.9613	.1107
Parietal	.9632	.0421	.9756	.0515
Occipital	.9881	.0493	.9999	.0498
Sleep Deprivation condition				
Day 1	Mean	SD	Mean	SD
Frontal	.9892	.0489	.9813	.0362
Central	1.019	.0643	1.026	.0543
Parietal	1.0027	.0574	1.035	.0343
Occipital	1.042	.0430	1.040	.0324
Day 2				
Frontal	.9453	.0319	.9508	.0282
Central	.9765	.0489	.9878	.0466
Parietal	.9834	.0561	.9949	.0461
Occipital	.9641	.0419	.9816	.0419

Appendix H

Table H1. A Spearman correlation was performed on Zeo scores, alpha frequencies (absolute) during eye closed at occipital sites and on τ. ($p<0.05$).

	Deep	Light	REM	Wake
Day1				
τ				
Block 1	.07	.153	-.122	.109
Block 2	.056	.301	.155	.052
Alpha				
Block 1	-.277	.367	.116	.156
Block 2	-.35	.207	.03	.076
Block 3	.074	.291	.379	.325
Day 2				
τ				
Block 1	-.09	.529*	.351	.245
Block 2	-.055	.418	.313	.05
Alpha				
Block 1	-.277	.367	.116	.156
Block 2	-.350	.207	.03	.076
Block 3	.074	.291	.379	.325

* $p<0.05$. ** $p<0.01$. *** $p<0.001$

Appendix I

Table I1. A Spearman correlation was performed on alpha frequencies (absolute) during eye closed at occipital sites and τ. (p<0.05).

	Alpha Block 1	Alpha Block 2	Alpha Block 3
Day1			
Sleep			
τ Block 1	-.261	-.285	.006
τ Block 2	-.298	-.255	.03
Sleep Deprivation			
τ Block 1	-.133	-.117	-.217
τ Block 2	.117	-.117	.183
Day 2			
Sleep			
τ Block 1	-.176	-.333	-.333
τ Block 2	-.079	-.207	-.207
Sleep Deprivation			
τ Block 1	-.201	.067	.067
τ Block 2	-.335	-.209	-.209

* p<0.05. ** p<0.01. *** p<0.001

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