CHAPTER 20

Understanding Brain Arousal and Sleep Quality Using a Neuroergonomic Smart Phone Application

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ABSTRACT

The increasing prevalence of mobile computer technology in everyday life allows for the collection of data that were previously inaccessible or expensive to obtain. Such data provide unique information different to that collected in the lab or through the use of questionnaires because they are obtained under naturalistic conditions—a requirement for neuroergonomics practice. Additionally, if users perceive the technology as either beneficial or enjoyable, longitudinal data become easier to collect. With these factors in mind, an iPhone application was developed to provide personalized feedback on sleep, sleep arousal, and variables that co-vary with sleep. The device included a vigilance task to measure arousal, an alarm clock to track sleep duration and time of sleep, and a diary that displayed sleep statistics to the user. The effect of sleep duration on vigilance task performance was investigated in a case study utilizing this device to collect naturalistic data. Three variations of the Psychomotor Vigilance Task (PVT) were administered, consisting of a 2 second window of response (for a total-time-on-task of 1 minute), 5-second window of response (for a total-time-on-task of 2.5 minutes), and 10-second window of response (for a total-time-on-task of 5 minutes). Performance efficiency on all three tasks was related to sleep deprivation. The results suggest that shorter duration tasks that require spatial discrimination and have higher motor demands than the conventional PVT are sensitive to the homeostatic component of sleep. Potential uses for this and similar applications to the field of neuroergonomics are also discussed.

INTRODUCTION

Neuroergonomics is an emerging field that combines neuroscience, human factors psychology, and engineering with the aim to optimize mental functioning during cognitive and physical work (Parasuraman, 2003). To accomplish this goal, work and brain function must be evaluated in naturalistic environments because there may be differences between behavior assessed in the laboratory and in real-world settings (Rizzo, Robinson, & Vicki, 2007).

The human brain arousal system has a major impact on work and health in general. There are many laboratory-based tests and questionnaires that have been used to assess arousal and human performance (Matthews, Davies, Westerman, et al., 2000). However, assessment techniques are needed that can be used with minimal training in naturalistic settings. Moreover, one goal of neuroergonomics is to use assessment of brain functioning to optimize mental functioning and performance in work or everyday settings. Towards that end, we developed a smart phone application that evaluates sleep in a naturalistic setting, analyzes the results, and then displays feedback designed to improve mental and physical functioning.

Insufficient sleep is prevalent. In 2007, the United States Department of Health and Human Services estimated that 64 million Americans regularly suffer from insomnia each year. Additionally, many more Americans intentionally go without sleep. The health and behavioral risk associated with sleep deprivation is severe, making this statistic particularly staggering.

Both simple and complex tasks are affected by sleep deprivation since performance decreases as sleep deprivation increases (Balkin, Rupp, Picchioni, et al., 2008). For example, epidemiological studies found an increased incidence of sleep-related crashes in drivers reporting six or fewer hours of sleep per night on average (Slutts, Wilkins, Osberg, et al., 2003). Studies also suggest that sleep is essential to higher-level cognitive processes such as processing sense of humor and learning new information (Thomas, Sing, Belenky, et al., 2000; Maquet, 2001).

Sleep deprivation also impacts health, where short-term effects include increased blood pressure, snacking on fatty foods, insulin resistance, and a weaker immune system. Furthermore, long-term effects of continual sleep deprivation are linked to higher rates of morbidity (Kripke, Garfinkel, Windegard, et al., 2002).

COMPONENTS OF SLEEP

The arousal system is regulated by three major components: (1) the homeostatic component, which is controlled by regions in the brainstem, such as the reticular formation, and serves to innervate the cortex in order to regulate sleep need, (2) the circadian component, which is instantiated by the interaction between hypothalamic oscillators in the suprachiasmatic nucleus of the hypothalamus and visual input, i.e.

light, and (3) sleep inertia, which is affected by sleep stage when awakened and is characterized by decreased cerebral blood flow after awakening from sleep. Understanding these components of sleep may promote healthier sleep decisions.

[1] Homeostatic Component

Sleep amount has a linear relationship with arousal. As the length of time awake increases, measures of arousal decrease. The rate of change in this relationship is dependent on various factors. For example, sleep need is a trait-like characteristic (Van Dongen, Baynard, Maislin, et al., 2004). Additionally, if sleep debt is high due to habitually sleeping for shorter periods, sensitivity to the effects of sleep loss increases (Balkin et al., 2008). However, there are general guidelines to sleep need where when sleep is routinely restricted to 7 hours or less, the majority of motivated healthy adults develop cognitive performance impairments; yet when nightly sleep periods are between 8-9 hours, no cognitive deficits are typically found (Mallis, Banks, & Dinges, 2008). Furthermore, at approximately 24 hours of sleep deprivation, the effects of sleep deprivation tend to plateau (Bonnet, 1991).

[2] Circadian Component

The circadian component interacts with the homeostatic component and has a sinusoidal relationship with arousal that peaks at around 3-5 p.m. (highest arousal) and troughs at around 2-4 a.m. (lowest arousal) in a 24 hour period (Dijk & Czeisler, 1995). Similar to the homeostatic component, this component is trait-like where "evening types" have a later shift in the circadian component and "morning types" have an earlier shift (Baehr, Revelle, Eastman, 2000). Additionally, environmental cues, called zeitgeber can influence this component of sleep. The strongest zeitgeber is exposure to light (Mallis, et al., 2008).

[3] Sleep Inertia

Sleep inertia is a third component of sleep that affects arousal after awakening from sleep and dissipates in an asymptotic manner that can take up to 4 hours (Jewett, Wyatt, Ritz-De Cecco, et al., 2008). However, the time course of sleep inertia is usually about a half hour (for a review see, Tassi & Muet, 2000). The severity of sleep inertia is largely affected by prior sleep deprivation and awakening from sleep near the circadian nadir (Naitoh, Kelly, & Bobkoff, 1993).

VIGILANCE

Typical vigilance tasks involve the detection of signals over a long period of time. The signals are intermittent, unpredictable, and infrequent. As the task progresses, performance steadily declines, and at about 10 minutes, task performance steeply declines (Davies & Parasuraman, 1982; Parasuraman, 1986; Boksem, Meijman,

Lorist, 2005). The steep decline is known as the vigilance decrement.

Wilkinson (1970) was the first to demonstrate that an auditory vigilance task is sensitive to sleep loss. Dinges and Powell (1985) then modified this task, and developed a 10-minute visual vigilance task called the psychomotor vigilance task (PVT). This task was found to be sensitive to all the components of sleep (Dinges, Orne, Whitehouse, et al., 1987; Van Dongen, et al., 2001). Vigilance tasks are more sensitive to the components of sleep than subjective measures of sleepiness and fatigue because people frequently underestimate the cognitive impact of sleep deprivation (Van Dongen, Maislin, Millington, et al., 2003).

The traditional explanation of this decrement is that it is due to boredom or motivation decline (Mackworth, 1968); however, another explanation of the vigilance decrement is that the workload associated with the vigilance task is high and that this depletes mental resources in a time-on-task driven manner (Warm, Parasuraman, Mathews, 2008). The latter hypothesis was recently supported by an fMRI study on the neural basis of the vigilance decrement, which showed that the vigilance decrement activated a right fronto-parietal attentional network that lateralized to the basal ganglia and sensorimotor cortices (Lim, Wi, Wang, et al., 2010). This activation was found after a time-on-task of about 20 minutes, which is longer than the typical PVT. Additionally, pre-task levels of CBF in the thalamus and right middle frontal gyrus were predictors of the vigilance decrement.

The 20 minute time-on-task required to detect the neural basis of the vigilance decrement suggests that the traditional 10 minute PVT may be activating cognitive processes other than those associated with the vigilance decrement. Indeed, performance on brief cognitive tasks that require speed of cognitive throughput, working memory, and other aspects of attention have been found to be sensitive to sleep deprivation (Mallis, et al., 2008) and these do not necessarily involve the vigilance decrement. However, like the PVT, tasks that measure sleep will have to be repeatedly administered without a learning effect.

Neuroergonomic Smart Phone Application

Technology to detect drowsiness in real-world environments must be unobtrusive to the user and able to calculate drowsiness in real-time (Mallis, et al., 2008). This requirement was met and exceeded in the development of the neuroergonomic smart phone application described here. A real time measure of drowsiness was evaluated using vigilance tasks and the application tracked sleep quality by integrating the vigilance task with an alarm clock. Furthermore, sleep quality and arousal is affected by more than just the components of sleep. Medication, drug use, food and caffeine intake, daily energy expenditure, and mood can also affect these tasks. This application can be used to measure these various factors that can affect sleep quality and arousal. User compliance was promoted by displaying these behaviors to the user in a manner that allows easy self-evaluation of behaviors. This can be used to adjust behaviors to improve cognitive performance. Detailed depictions of the application can be found at www.proactivesleep.com.

[1] Tracking Sleep

In order to assess sleep quality, an alarm clock was integrated in the application where sleep onset was estimated based on setting the alarm. Pressing either <wake naturally> or <set alarm> brings up another screen where a button can be pressed to indicate if the user is permanently awakened. This enabled for the tracking of sleep without needing the alarm to go off. Additionally <wake naturally> enabled users to use the application without setting an alarm. When the alarm goes off or <permanently awakened> is pressed, the vigilance task is triggered. Awakening from sleep is determined by when the user completes the task.
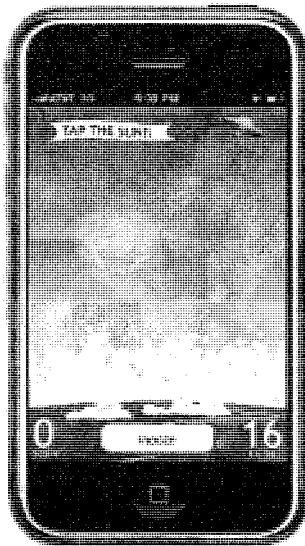
[2] Vigilance Task

Figure 1. Vigilance Task

In this task a stimulus, in this case, a sun, randomly appeared at a location on the screen for 1.5 seconds (see Figure 1). When the sun appeared, users were instructed to tap on it as quickly as possible. There were three variations of this tasks included. These tasks differed in the time duration of the stimulus onset window or in other words, in the time interval that the stimulus may appear. This time interval was either short (2 seconds), medium (five seconds), or long (ten seconds). Thus, in the short condition there was a higher frequency of motor activity, but in the long condition the onset of the stimulus was more unpredictable. This means that the long condition more in line with typical vigilance tasks. All tasks had 30 trials, resulting in the short task lasting 1 minute, the medium task lasting 2.5 minutes, and the hard task lasting 5 minutes.

[3] Usability

The sleep diary is the feedback mechanism that provided users with information on there behaviors (see Figure 2). In this version, the behaviors were sleep related, but other versions may include information on other behaviors,
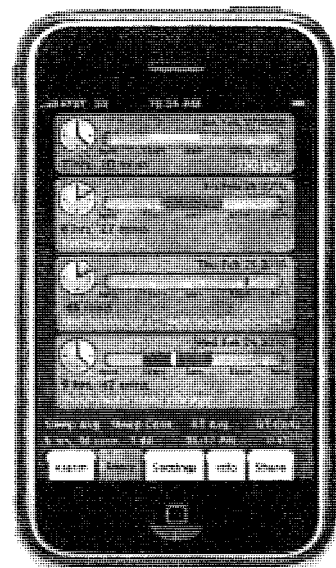

Figure 2. Sleep Diary

like mood, exercise, and diet. Gestalt based color principles were used in this interface where green indicates healthy behavior, yellow indicates warning, and red indicates danger. Additionally, both daily behavior (each individual entry) and average behavior (see the bottom of Figure 2) were displayed to the user. The colored bars for each entry display sleep duration and time of sleep, which can be edited. The color represents sleep amount, where users set a sleep goal and the colors indicated if they were meeting, almost meeting, or not meeting the goal. The clock icons corresponded to the result of a question about how long it took to fall asleep. Again, how long it took was represented by the color of the response, and additionally, reinforced by more time on the clock. Performance on the vigilance task was also displayed to users (see upper right of Figure 2) and users could write additional notes about sleep or other behaviors that were displayed below entries.

METHOD

[1] Participants

Twenty-five George Mason University undergraduate students participated for course credit. All participation was voluntary. Participants were required to own either an iPhone or an iPod-touch running the 3.0 operating system or higher.

[2] Design and Procedure

The sleep diary was disabled in order to promote experiment control and each participant was randomly assigned to one of three vigilance task conditions: short window of response, medium window of response, and long window of response.

Email was the only medium used to communicate with participants. After signing up for the study, instructions were provided on downloading the application to an iPhone or iPod-touch device and how to use the application. Participants were instructed to go to the settings tab and select which vigilance task would be administered by pressing one of three buttons. After completing this task, participants were told not to enter the settings screen again.

Participants were given an overview of how to interact with the application. It was emphasized that participants should not deviate from their normal sleeping patterns. After the overview, participants completed a practice session using the device. In this practice session, they were instructed to set the alarm, press the <set alarm> button, and then press <permanently awakened>. This prompted the idle screen of the vigilance task and participants were told the objective of the task, which was to tap the image of the sun as quickly as possible. Then participants were told to press the <start game> button, and instructed to complete a session of the game.

The actual task consisted of setting the application at night and playing the vigilance task upon awakening from sleep. The task lasted for three weeks. One day using the application entailed setting the alarm by pressing <set alarm> or

<wake naturally>, sleeping, and playing the vigilance task when the alarm is triggered, which when completed, shuts off the alarm music and phone vibrator. Another option available to the participant when the alarm is set is to press the <snooze> button, which results in a ten-minute delay before the alarm goes off again. All data was collected using the Google App Engine. This system acts as a server for smart-phone applications. Thus, any interaction that users have with the application can be exported to the server provided that the Google App Engine script is embedded in the application and the device has Internet connection.

[3] Measures

Sleep onset was determined based on when <set alarm> or <wake naturally> was pressed and awakening was determined when the vigilance task was completed. From this, sleep duration was estimated. Consistent with how PVT performance is typically assessed, measures were taken on the fastest 10% of reaction times, the slowest 10% of reaction times, and misses (Dinges et al., 1985).

RESULTS AND DISCUSSION

Four subjects were eliminated because they had less than seven entries of sleep data, which resulted in twenty-one total participants. There were seven participants in each condition, resulting in 69 entries for the short window condition, 85 entries for the medium window condition, and 76 entries for the long window condition. The number of entries per subject ranged from seven to twenty-one. Only sleep durations of more than two hours were included in the analyses because the aim of this study was to investigate the effects of at least a night of sleep.

A between subjects ANOVA was run to check that sleep durations did not systemically vary across the three conditions. Results suggested sleep duration was not different between the short window condition ($M = 7.63$ hrs, $SD = 1.60$ hrs), medium window condition ($M = 7.50$ hrs, $SD = 1.94$ hrs), and long window condition ($M = 7.10$ hrs, $SD = 2.10$ hrs), $F(2, 229) = 1.60, p = .20$.

In order to understand the relationship between sleep duration and task performance, sleep duration was mean centered around the participant's average duration of sleep. The reasons for this were that sleep need shows considerable inter-individual variability and because it was necessary to compare sleep duration between participants. Pearson correlations were then run between sleep duration and the three performance measures (10% fastest RTs, 10% slowest RTs, and misses) across all three conditions (see Table 1).

Table 1. Pearson Correlation Table Between Sleep Duration and Vigilance Performance.

Variables	Fastest 10% RT	Slowest 10% RT	Misses
Sleep Dur. Short Window (N = 69)	-.25**	-.24*	-.22†
Sleep Dur. Medium Window (N = 85)	-.26*	-.06	.27*
Sleep Dur. Long Window (N = 76)	-.37**	-.24*	-.42**

† $p < .10$. * $p < .05$. ** $p < .01$.

There was a consistent trend where as sleep duration increased, performance on all three vigilance tasks improved. This improvement in task performance involved decreased 10% of fastest and slowest reaction times to detect the stimulus and decreased misses when detecting the stimulus. Based on Cohen's guidelines, all of the correlations were in the medium effect size range, with the exception of slowest 10% of reaction times in the medium window task.

GENERAL DISCUSSION

The results of this study show that effects of sleep quality on performance can be detected under naturalistic conditions using smart phone technology. As such the design application described here represents an example of a neuroergonomic assessment technique that can be used with minimal training by users in their everyday lives. The smart phone application we developed evaluates sleep in a naturalistic setting, analyzes the results, and then displays feedback to the user. Such feedback could be used by users themselves to monitor and if necessary improve their mental and physical functioning.

A neuroergonomic application centered on the human arousal system may be an important step in addressing the widespread and severe problem of inadequate sleep. This application provides unique data related to the arousal system because it can be administered in naturalistic setting. The data can predict task performance, which may be especially useful for designing job schedules that have erratic hours (i.e., doctors and pilots). Additionally, since behavioral treatments play a role in alleviating many sleep and mood disorders (Mori, Bootzin, Buysse, et al., 2006), this application may be a vehicle for monitoring the efficacy of clinical treatments.

The evaluation study found that all three versions of the vigilance task were sensitive to sleep duration, although the degree of sensitivity varied with task type. In particular, the finding that even the 1-minute task was sensitive to sleep duration is notable. The longer the duration of a vigilance task, the less likely that participants and users will be compliant and finish the task when testing themselves in their everyday routine. Thus, a short-duration task will promote more repeated use of the application.

We did not obtain evidence of vigilance decrement in any of the three task

conditions. While under certain conditions the vigilance decrement can occur after as little as 5 minutes of continuous work (Nuechterlein, Parasuraman, Jiang, 1983), the necessary task conditions (low target salience or high working memory load) were not features of the task used in the present application. The findings suggest that the vigilance decrement is not a requirement to detecting the homeostatic component of sleep

A future research direction is to determine if other tasks may be more sensitive to the detection of arousal. Tasks that involve the prefrontal cortex, which implicates divergent thinking and working memory, are also adversely affected by sleep loss. (Mallis, et al., 2008). Furthermore, a vigilance task developed by Cagglano and Parasuraman (2004) involved the dual processes of signal detection of a spatial location and working memory. Such a task may be a stronger predictor of the components of sleep.

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