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# Objective Measurement of Sleep by Smartphone Application: Comparison with Actigraphy and Relation to Cognition, Mood, and Self-Reported Sleep

Taylor R. Maynard

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Running head: OBJECTIVE MEASUREMENT OF SLEEP

Objective Measurement of Sleep by Smartphone Application: Comparison with Actigraphy and  
Relation to Cognition, Mood, and Self-Reported Sleep

Taylor R. Maynard

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Dr. Sandy Nearing, Thesis Director  
Dr. Nesa Wasarhaley, Committee Member  
Dr. Michael Root, Committee Member

## Abstract

Over the past six decades, polysomnography, actigraphy, and most recently smartphone technology have created a trifecta of options for measuring sleep. It remains to be seen whether smartphone applications are comparable to actigraphy in objectively monitoring sleep. The present study had 29 healthy adult participants fill out a sleep diary and use the Sleep Time app (Azumio, Inc.) to monitor their sleep for one week. A subset of 19 participants also wore an actigraphy bracelet. Self-report questionnaires characterized sleep habits and psychological profiles of participants, while cognitive assessments were implemented to examine potential correlations between total sleep time (TST) and/or sleep efficiency and executive functioning. The smartphone app overestimated TST when compared to actigraphy, yielding a significant difference,  $t(18) = -6.64, p = .01, r^2 = .71$ . Moreover, a statistical trend indicated that the app also overestimated sleep efficiency,  $t(18) = -2.06, p = .06, r^2 = .12$ . There were no correlations between self-reported sleep quality and performance on cognitive tasks or total number of caffeinated beverages consumed in this sample. Overall, results show that this smartphone app is not accurate in monitoring TST or sleep efficiency when compared to actigraphy. Future research is needed to investigate the utility of smartphone applications in monitoring sleep in clinical populations and across other smartphone apps and phone models.

Objective Measurement of Sleep by Smartphone Application: Comparison with Actigraphy and Relation to Cognition, Mood, and Self-Reported Sleep

**Introduction**

A human spends one third of their life asleep which equates to 25 years spent sleeping (Heppner, 2015). According to the National Heart, Lung, and Brain Institute (2012) sleep duration and quality of sleep protect and improve physical health, mental health, safety, and overall quality of life. In addition, Wilckens, Erickson, and Wheeler (2012) state that deep sleep (also known as slow-wave sleep) can substantially benefit the functioning of the prefrontal cortex (PFC) and can consequently contribute to normal cognitive functions such as working memory, inhibition, and controlled memory processes.

Approximately 70 million Americans are affected by sleep disorders with 90 individual sleep disorders identified in the literature (Colten & Altevogt, 2006). Sleep disturbances that result in impairments during the daytime are frequently reported in adults (Stepanski, Rybarczyk, Lopez, & Stevens, 2003). One of the most dangerous impairments that can result from sleep deprivation and fragmentation is lack of wakefulness during driving; without proper sleep hygiene, the likelihood of drowsiness, mental fatigue, and falling asleep at the wheel are heavily increased (Goel, Hengyi, Durmer, & Dinges, 2009). Furthermore, motor sequence acquisition in younger adults over the age of 18 can also become impaired due to poor sleep quality (Appleman, Albouy, Doyon, Cronin-Golomb, & King, 2015). Bonnet (1986) reported that poor quality of sleep or lack of long periods of uninterrupted sleep produces adverse effects on cognitive performance and motor functioning during the daytime hours. This sleep deficit can significantly contribute to the occurrence of falls and accidents, lack of concentration, memory impairment, proper limbic system functioning, and the ability to complete daily tasks. Baglioni,

Spiegelhalter, Lombardo, and Riemann (2010) claim that disturbances in sleep have yielded a number of detriments, including emotional reactivity and poor emotion regulation that are problematic to mental health.

Monitoring sleep could easily become an integral part of treatment in the field of rehabilitation psychology, which works to apply skills, knowledge, and technology to improve the health and wellbeing of individuals suffering from various diseases and disabilities. The standard methods used to evaluate sleep variables such as total sleep time (TST), sleep efficiency, and stages of sleep have blossomed in sync with technological advancement over the years, beginning with the evolution of polysomnography (PSG) throughout the 1960s and 1970s (Haba-Rubio & Krieger, 2012), actigraphy in 1988 for the United States military (Actigraph, 2016), and finally the incorporation of accelerometer technology in smartphones during recent years.

### **Polysomnography**

Today, PSG continues to be the gold standard for objective measurement of sleep. PSG consists of continuous monitoring of variables of neurophysiology and cardio respiration via electrodes that are connected to the body. PSG sleep studies are typically conducted over the span of one night for the purpose of monitoring both disturbed and normal sleep in the context of sleep apnea or general sleep impairments (Bloch, 1997). Since 1997, it has become increasingly common for PSG sleep studies to require more than just one night of sleep monitoring (e.g., Jarrin et al., 2016). Despite how common overnight sleep studies are, some researchers are skeptical of whether external factors (for example, a laboratory setting) can impact the validity of study results. For instance, Iber and colleagues (2003) questioned the external validity of sleep studies and postulated that body position (while in bed), alcohol consumption, sleep stage

distribution, and sleep duration may all play a significant role in subjects' sleep patterns and quality. Iber et al. (2003) also state that within-laboratory or within-home sleep monitoring as well as the degree of supervision of monitoring could potentially affect physiologic parameters of sleep. From a broader perspective on PSG that falls outside of sleep apnea studies, it is imperative to look not just at the effects of location on data outcomes, but also on individual comfort levels that could consequently affect the data. Siversten et al. (2006) asserts that PSG can be invasive, expensive, and time-consuming. Other alternatives, such as wrist actigraphy technology, may be a comfortable and inexpensive substitute for traditional PSG monitoring, depending on patients' needs and preference.

### **Actigraphy**

Actigraph technology can be set apart from PSG monitoring, as it allows the convenience and comfort of wearing the device as a watch-like bracelet on the non-dominant wrist or ankle, directly in contact with the body, and within one's typical environment, thereby increasing its external validity. Actigraphy has been used to measure sleep for the purpose of research for over two decades (Mantua, Gravel, & Spencer, 2016). An actigraph is constructed with an acceleration sensor that can translate physical motion into a numeric representation measured in epochs (e.g., minutes; Sadeh, Hauri, Kripke, & Lavie, 1995). Furthermore, the actigraph is expedient in the way that the data can be easily extracted from the bracelet and transferred onto a computer via an actigraph dock and USB adapter. Actigraphs are waterproof and thus do not need to be removed at any point during studies, allowing for continuous data collection (Sadeh et al., 1995). A recent study on the effectiveness of actigraph technology demonstrated that actigraphy data corresponds significantly with PSG data in a sample of both young and older adults (Kosmadopoulos, Sargent, Darwent, Zhou, & Roach, 2014). Welk, McClain, Eisenmann,

and Wickel (2007) posit that the accelerometers built within actigraphs offer promising calculations of movement and exerted energy, and since the 1980's, researchers have been employing actigraphy as a reliable means of quantifying physical activity (Dinesh & Freedson, 2012). Likewise, wearable technology such as the Fitbit (Fitbit, Inc., San Francisco, CA, USA) is becoming ubiquitous in Western society (Zambotti et al., 2016).

Despite supportive and validating research on actigraphy technology, Verbeek et al. (1994) found that actigraphy has been shown to overestimate TST in comparison to PSG. However, Martin and Hakim (2011) claim that in recent studies, actigraphy bracelets have been valuable in calculating both TST and sleep efficiency, despite the prior findings (from 1994) of overestimation.

### **Smartphone Applications**

Today, there is a vast variety of free smartphone apps that are used to monitor individuals' health, diet, fitness, and smoking habits. Apple, Inc. proclaimed in a 2009 television commercial that "There's an app for that," regarding the creation of countless smartphone applications (many of which were free to use standard features) that yielded a plethora of uses (including healthcare) to people around the world (Bhat et al., 2015; CommercialKid et al., 2009). Consequently, the creation of smartphone apps that monitor and evaluate the quality of one's sleep and its duration have been marketed through app stores for use on smartphones and other mobile devices, such as smartwatches and tablets. Batista and Gaglani (2013) suggest that the potential for a new frontline of clinical practice and research is being offered by the prevalent use of advanced smartphone technology.

One such example of a smartphone application that could be utilized in both healthy and clinical populations is the Sleep Time smartphone app (Azumio, Inc., Palo Alto, CA, USA). Bhat

and colleagues' 2015 study compared sleep efficiency, sleep latency, and light sleep/deep sleep percentages recorded through the Sleep Time app to those recorded through PSG. Correlations between sleep data collected through the app and through PSG were found to be weak. Further research could compare both sleep efficiency and TST recorded through the app to data recorded through actigraphy technology. Contingent upon future research findings, the Sleep Time app could be a cost-efficient and innovative alternative to the expensive and invasive use of overnight PSG monitoring or even the in-home use of clinical devices like actigraphy.

Younger and more tech-savvy clinical populations may prefer to use smartphone applications that record their sleep data, rather than to fill out a daily sleep diary when asked to by their doctor. Likewise, those who wish to have their sleep data in real time and at their disposal might prefer a smartphone app to actigraphy, which does not immediately display a previous night or week of sleep without first returning to a doctor's office or research laboratory for data extraction. There are a variety of clinical populations that could benefit from technological sleep tracking methodologies, such as adults with insomnia, narcolepsy, sleep apnea, or other sleep disorders. Older adult populations with cognitive deficits or neurodegenerative diseases could also make use of smartphone applications that track their sleep, as poor sleep quality is often a co-occurring symptom of diseases such as Alzheimer's and Parkinson's disease (Vitiello, Poceta, & Prinz, 1991).

### **Effects of Sleep on Cognition and Mood**

Given that sleep hygiene is an integral part of functioning at one's best, poor sleep quality and sleep deprivation can be culprits of weaker waking neurobehavioral functioning, such as slowed working memory, reduced cognitive ability, lapses of attention, and depressed mood in both middle-aged and older healthy adults (Banks & Dinges, 2007; Sutter, Zolig, Allemand, &



Martin, 2012). Moreover, Van Dongen et al. (2003) and Wilckens et al. (2014) demonstrated that sleep continuity and TST impact executive functioning across the lifespan, while Yoo, Hu, Gujar, Jolesz, and Walker (2007) showed that sleep is integral for encoding memories and consolidation following learning. In addition, Baglioni et al. (2010) and Leotta, Carskadon, Acebo, Seifer, & Quinn (1997) suggest that sleep deprivation and fragmented sleep are associated with negative emotional consequences, such as fluctuations in emotional reactivity. Thus, being mindful of the amount and quality of one's sleep can be useful for functioning in the best capacity.

### **Effects of Caffeine on Sleep Quality**

Sleep quality can be negatively impacted by various disorders and lifestyle factors, such as psychological distress, gastroesophageal reflux disease (GERD), lack of exercise, poor socioeconomic status, and caffeine consumption (Baker, Wolfson, & Lee, 2009; Shaker, Castell, Shoenfeld, & Spechler, 2003; Soltari et al., 2012). In particular, caffeine consumption, contingent upon a given individual's dose and the time of day, has been shown to significantly hinder total sleep time, perceived quality of sleep, and sleep onset (Hindmarch et al., 1999; Penetar et al., 1993; Smith, Maben, & Brockman, 1993). Lotan et al. (2002) elaborates on this literature, recommending that individuals diagnosed with sleep disorders or those experiencing sleep abnormalities should especially avoid caffeinated beverages during the evening.

### **Current Project**

The current project compared data collected objectively by the Sleep Time app (Azumio, Inc., Palo Alto, CA, USA) to data recorded from actigraphy bracelets worn by participants recruited from individuals known to members of Boston University's Vision and Cognition Laboratory. Sleep diaries from the National Sleep Foundation as well as self-reported

questionnaires were utilized to gather subjective data from participants. The primary variables of interest were total sleep time (TST) and sleep efficiency; both the Sleep Time app and actigraphy bracelets monitored and measured TST in minutes and sleep efficiency as a percentage. TST is the calculation of the total number of undisturbed minutes that an individual sleeps, while sleep efficiency is a percentage of the amount of time that an individual is experiencing undisturbed sleep (i.e. they are not experiencing fragmented or restless sleep). Furthermore, differences between objective data generated from the Sleep Time app and actigraphy as well as subjective self-report sleep measures completed by participants were examined. Participant-completed sleep diaries were used in conjunction with the Sleep Time app and actigraphy to control for potential malfunction or noncompliance with either the actigraph or the app. Subjective sleep measures were used to account for when actigraphy overestimated TST in individuals that may have had trouble falling asleep at night but whom remained motionless in their beds (Martin et al., 2011). Thus, self-report measures were integral to lending the most accurate data possible to the project. In addition, participant scores from two assessments of executive functioning and two self-report measures of mood were analyzed to examine a potential interplay of sleep quality and sleep duration with cognition and mood. Lastly, participants' total number of caffeinated beverages were statistically compared to their self-reported ratings of sleep quality in order to examine a potential relationship between the two.

Hypotheses for the study include the following: 1) Self-report information recording TST as obtained by sleep diaries will differ from objective information on TST as collected by the Sleep Time app; 2) Self-reported sleep quality will positively correlate with performance on tasks of executive functioning and working memory, and negatively correlate with self-reported scores of perceived depression or anxiety; 3) Self-reported sleep quality will negatively correlate

with total number of caffeinated drinks consumed by each participant over the course of one week; 4) There will be a significant difference between means of TST and sleep efficiency as recorded by the Sleep Time app and actigraphy bracelets. Comparing means on the two variables of sleep could lend credence to the idea that the Sleep Time app can be used as a valid objective method of measuring sleep if no significant differences are found.

## **Method**

### **Participants**

The current project collected and examined both subjective and objective data from 29 healthy adult volunteers ranging from 20 to 67 years ( $M = 26.8$  years,  $SD = 11.7$  years). The project was publicized through convenience sampling (i.e. word-of-mouth and social media technology). Screening questionnaires were administered to interested adults to determine individual eligibility (see Appendix A). If screened individuals were free of acute or chronic medical conditions and sleep disorders (e.g. obstructive sleep apnea, restless leg syndrome, clinical insomnia, etc.), and were not taking any prescription or over-the-counter sleep medications, they were queried and included in the study. Additionally, participants made sure to have access to an iPhone with IOS 8.0 or later for the daily use of the Sleep Time app (a free download in the Apple store).

### **Measures and Procedures**

Written informed consent of each participant was obtained on the day of their first study visit. This study was approved by the Institutional Review Board (IRB) of Boston University. Once informed consent was obtained during the first study visit, participants were given a paper sleep diary from the National Sleep Foundation and downloaded the Sleep Time app on their smartphone device. In addition to filling out a daily sleep diary and using the Sleep Time app, 19

out of the 29 participants also agreed to wear an actigraphy bracelet for one week. All 29 participants returned for a second study visit, when five self-report questionnaires and two cognitive tasks were administered. Among the five questionnaires was an exit questionnaire that reflected the app's feasibility and likelihood of individual use in the future. Each of the other questionnaires and the two cognitive tasks are further described below.

### **Self-report measures of mood.**

*Beck Depression Inventory II (BDI-II).* The BDI-II (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961) was administered upon each participant's second study visit. This 21-question self-report mood metric of depression was employed to gather data on perceived symptoms of depression; each answer provided is scored on a scale of 0-3. The dependent variable of the BDI-II is the total score out of 21 questions. A score range of 14-19 suggests that the individual experiences mild depression, while a score of 29-63 suggests severe depression; thus, the lower the overall score, the better an individual's mood.

*Beck Anxiety Inventory (BAI).* The BAI (Beck, Epstein, Brown, & Steer, 1988) was also completed by participants during the second study visit. The BAI is a 21-question self-report mood metric of anxiety, utilized to gather data on subjective symptoms of anxiety. Each answer provided is scored on a scale of 0-3, with a score of 0 indicating that the individual does not experience a specific symptom of anxiety at all, while a score of 3 indicates that an individual is frequently bothered by a particular symptom. The dependent variable of the BAI is the total score out of 21. A score of 0-9 suggests minimal anxiety while a score of 30-63 suggests severe anxiety; thus, the lower the overall score, the better an individual's mood.

**Self-report measures of sleep.**

*Epworth Sleepiness Scale (ESS)*. The ESS (Johns, 1997) is a questionnaire that provided subjective information about one's perceived daytime sleepiness across eight different situations of everyday life, such as reading, watching TV, or being in a car during traffic. Participants rated themselves on a scale of 0 ("would never doze") to 3 ("high chance of dozing") across eight situations of everyday life. The ESS asks for responses that reflect the most recent way of living. Each test's eight responses (0-3) are totaled (dependent variable). Any total score over 10 signifies the presence of excessive daytime sleepiness, indicating the possibility of a clinical sleep disorder.

*Pittsburg Sleep Quality Index (PSQI)*. The PSQI (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) is a 19-item self-report questionnaire that collects subjective information about participants' sleep quality over the course of the past month. The global score of the PSQI can fall in the range of 0-21, and is calculated through seven component scores, with each question weighted on an interval scale of 0-3. The higher an individual's score, the poorer their sleep quality. The current study compared general sleep quality data as reported by a single PSQI question (about overall sleep quality) to performance on cognitive assessments.

**Measures of executive functioning.**

*Letter-Number Sequencing*. Letter-Number Sequencing is a cognitive measure from the Wechsler Adult Intelligence Scale IV (Wechsler, 2008) that assesses participants' attention, concentration, short-term auditory memory, sequential processing, memory span, and mental manipulation. Individuals first listen intently to the assessors as they read aloud a random sequence of letters and numbers; the individual is instructed to repeat the sequence back to the assessor by first listing the given numbers in order, followed by listing the letters alphabetically.

The Letter-Number Sequencing assessment consists of ten test items with three trials per item. Each trial is scored with either 0 or 1 point; a total of 3 points can be earned per test item. Once a score of 0 is earned for an entire test item, the assessment is discontinued and all scores from the completed test items are added together for one sum score (dependent variable), ranging from 0-30. In addition, a longest letter-number sequence score (dependent variable) is calculated, given the total number of letters and numbers in one sequence that the participant was able to accurately recall; this score can range from 0-8.

***Verbal fluency (FAS and category-animals).*** The FAS verbal fluency assessment is one form of the Controlled Oral Word Association (COWA) Test (Benton, Hamsher, & Sivan, 1983). The FAS is a free-recall task which instructs individuals to name as many words as they can (excluding proper nouns) beginning with the letters F, A, and S (phonemic processing) within a one-minute time period, excluding any proper nouns or different forms of the same words, such as “big,” “bigger,” and “biggest.” The number of words recorded in 15-second increments of time is also noted to easily examine cognitive clustering. In addition, naming as many animals as possible (semantic processing) in a one-minute time frame was included in this assessment to further measure executive functioning. The dependent variable is the total number of acceptable words produced within each one-minute period of time.

### **Objective measures of sleep.**

***ActiGraph GT9X Link by Actigraph.*** For a continuous period of one week, a subset of 19 out of 29 participants wore the Actigraph GT9X Link watch on their non-dominant wrist. Movement during wake and sleep time was recorded through accelerometer technology for 24 hours a day. The dependent measures examined were averages of each participant’s seven days of calculated TST (in minutes) and sleep efficiency (percentage).

*Sleep Time (Azumio, Inc.) smartphone application.* The Sleep Time app (Azumio Inc., Palo Alto, CA) was utilized by participants to monitor their sleep. The free version of this smartphone app is available in the Apple App Store. The current model of this application is 5.28 (updated 05/12/2016). TST and sleep efficiency was monitored and recorded with this app; daily TST minutes and sleep efficiency percentages were averaged for each participant, based on the seven days of use.

### **Subjective measures of sleep.**

*National Sleep Foundation sleep diary.* Provided for free by the National Sleep Foundation (2016), sleep diaries were administered to all participants to fill out each morning and night for seven days for several different purposes. The diary accounted for actigraph and Sleep Time app malfunctioning and noncompliance. Self-reported TST and sleep quality were analyzed in addition to certain aspects of participants' daytime and nighttime routines, including caffeine consumption, exercise, activities before bedtime, and prescription medications. Each item on the sleep diary was assigned a numerical value (0-7, depending on the kind of questions) for use in correlational analyses, and other participant responses were recorded verbatim in the database for qualitative use.

### **Ease of use and likelihood of future use.**

*Exit questionnaire.* Participants filled out an exit questionnaire during their second study visit that asked about subjective lifestyle factors such as the type of mattress they use and whether or not they sleep with pets in their beds. In order to gather data on participants' subjective opinions of using the Sleep Time app to monitor TST and sleep efficiency in the future, participants were asked to rate the app's ease of use as well as the likelihood that they would use the app again in the future. Correlational analyses were conducted to examine whether

ease of use correlated with likelihood of future use as well as to see if age played a role in ease of use.

### **Data Analysis**

TST and sleep efficiency data were extracted from the actigraphs and the Sleep Time app and each participants' seven days of data were averaged for each methodology. Paired samples *t*-tests were performed and effect sizes were calculated to determine significant differences between TST and sleep efficiency as recorded through actigraphy and the smartphone application. Additionally, Pearson correlation analyses were executed to identify potential correlations between self-reported sleep quality and performance on two cognitive tasks that assessed executive functioning and working memory. The sleep data were also correlated with certain variables, such as caffeine consumption, from the administered self-report sleep and mood questionnaires.

## **Results**

### **Subjective vs. Objective TST Data**

It was initially hypothesized that self-report information recording TST as obtained by sleep diaries would differ from objective data on TST as collected by the Sleep Time app. A paired samples *t*-test indicated that there was not a significant difference between TST recorded by the app ( $M = 441, SD = 75.6$ ) and TST recorded in the sleep diaries ( $M = 437, SD = 73.8$ ),  $t(10) = .31, p = .77$ .

### **Effects on Cognition and Mood**

The second hypothesis predicted that self-reported sleep quality would positively correlate with performance on tasks of executive functioning and negatively correlate with self-reported scores of perceived depression or anxiety. There were no correlations between self-



reported sleep quality and performance on cognitive assessments. No significant correlations between scores on the BDI-II and BAI and TST or sleep efficiency were observed, though individuals' scores on the BDI-II and the BAI were positively correlated, Pearson's  $r(23) = .43, p = .03$  (see Table 1). In addition, age positively correlated with BDI-II scores, Pearson's  $r(23) = .54, p = .01$  such that older participants had higher scores on the BDI-II (see Table 1).

### **Self-reported Sleep Quality and Caffeine Consumption**

The third hypothesis postulated that self-reported sleep quality as measured by the ESS would negatively correlate with the total number of caffeinated drinks consumed by each participant over the course of one week. Findings from a Pearson correlation analysis show that there were no significant correlations between total number of caffeinated drinks consumed by each participant and self-reported sleep quality, Pearson's  $r(29) = .25, p = .19$  (see Table 1), contrary to the initial hypothesis and findings in prior literature.

### **TST and Sleep Efficiency**

The fourth hypothesis stated that TST and sleep efficiency as recorded through the Sleep Time app would significantly differ from sleep data recorded through actigraphy. A paired-samples  $t$ -test showed that the smartphone app overestimated TST when compared to actigraphy, thus yielding a significant difference,  $t(18) = 6.64, p = .01$  (see Figure 1). More specifically, the smartphone app overestimated TST 100% of the time for 68% of the total sample. The remaining 32% of participants yielded data showing that the app overestimated TST anywhere from 20%-86% of the time. See Table 2 for a detailed representation of how much each participants' smartphone app overestimated TST. Moreover, a statistical trend indicated that the smartphone app also overestimated sleep efficiency when compared to actigraphy,  $t(18) = 2.06, p = .06$  (see Figure 2). The smartphone app overestimated sleep efficiency 100% of the time for 26% of the total population of participants who used the app and the actigraph, while another 16% of

participants provided data that showed that the app overestimated sleep efficiency 80% of the time. The other 58% of this population yielded data showing that the app overestimated sleep efficiency anywhere from 14%-60% of the time. For a detailed visual of how much each participants' smartphone app overestimated sleep efficiency, see Table 2.

### **Exploratory Findings**

*Self-reported app use.* Participants' self-reported ease of use of the smartphone app positively correlated with their likelihood of future use, Pearson's  $r(27) = .47, p = .01$  (see Table 1). No other significant correlations between age, ease of use, and likelihood of future use were found (all  $p$ 's  $> .83$ ).

### **Discussion**

This study investigated the utility of a smartphone application in monitoring sleep in healthy adults in comparison to actigraphy technology. Potential correlations between sleep efficiency and performance on tasks of executive functioning and mood metrics were examined, in addition to that of caffeine consumption and self-reported sleep quality.

The first hypothesis stated that self-report information recording TST as obtained by sleep diaries would be significantly different from objective TST data collected by the Sleep Time app, due to the idea that participants may not be the most accurate self-reporters of their own sleep. The results of a paired-samples  $t$ -test refuted this hypothesis, as there were no significant differences between subjective data recorded in sleep diaries and objective sleep data collected by the Sleep Time app. This finding suggests that the Sleep Time app, when compared to subjectively recorded TST, is an accurate predictor of TST in a healthy adult sample; however, it is important to consider that participants, despite being given specific directions, may

have recorded their Sleep Time app data into their sleep diaries, which could account for the lack of difference.

The second hypothesis predicted that subjective sleep quality would positively correlate with performance on tasks of executive functioning and working memory in addition to self-reported scores of perceived depression or anxiety; this hypothesis was not supported by the present study. Contrary to prior literature suggesting that even moderate sleep deprivation can have a negative impact on neurobehavioral and cognitive functioning (Van Dongen et al., 2003), the present study did not find significantly negative effects of TST and sleep efficiency on cognition or mood in a healthy adult sample; however, self-reported sleepiness may be related to additional self-report metrics of mood and sleep. Perhaps a larger sample size and broader range of ages and sleep quality would yield results akin to that of Van Dongen and colleagues' (2003) findings, as a sample size of 29 may not hold enough power to detect this relationship. In regards to the effect of sleep quality on mood, a study on sleep fragmentation in a healthy adult population revealed that individuals whose sleep continuity (slow-wave sleep) was disrupted had a significantly negative impact on mood compared to those who delayed their bedtime and consequently had smaller amounts of TST (Finan, Quartana, & Smith, 2015). Based on Finan and colleagues' (2015) findings, later directions in sleep research should further investigate the effects of slow-wave sleep disruption on mood within clinical populations. Establishing the importance of sleep continuity in both healthy and clinical populations could offer new insights into the development of new sleep-tracking devices as well as improvement of current devices such as smartphone applications and wrist watches.

The third hypothesis postulated that there would be a negative correlation between self-reported sleep quality and total number of caffeinated beverages consumed over the course of

one week for each participant. Contrary to the initial prediction, and findings in prior literature, no significant correlation was found; in part, this may be due to the fact that the time of day during which participants consumed caffeinated beverages was not investigated in the analysis. In a study by Drake, Roehrs, Shambroom, and Roth (2013), caffeine consumption was shown to be significantly detrimental to sleep quality when consumed 1-6 hours prior to bedtime. Thus, future research in this area should continue to measure various population's response to caffeine intake during evening hours.

The final hypothesis predicted that there would be a significant difference between the means of TST and sleep efficiency as recorded by the Sleep Time app and actigraphy bracelets. Supporting this hypothesis and consistent with the little literature that tested the utility of the Sleep Time app, significant differences were found between the two sleep-tracking methodologies, as calculated through paired-samples *t*-tests. This suggests that the Sleep Time app is not a valid measure of TST and sleep efficiency in a healthy adult population. Bhat and colleagues (2015) arrived at similar results when assessing the utility of the Sleep Time app in monitoring sleep efficiency and other sleep variables when compared to overnight PSG sleep monitoring. Despite the prior findings, the present study further tested the Sleep Time app by monitoring TST and sleep efficiency and comparing it to data collected through actigraphy.

Future directions in smartphone and wearable, sleep-tracking technology should aim to adopt standard metrics for validation of these devices in order to inform both the research world as well as companies interested in marketing their devices for research and clinical applications. Relatedly, Zambotti and colleagues (2016) stress that there is a pressing need for active communication between the sleep research community and companies that market wearable technology, so that marketing output of these devices can be optimized; this would endorse the

implementation of commercial sleep-tracking devices in both clinical and laboratory settings as a cost-efficient option for researchers, patients, and doctors.

Currently, there is insufficient evidence to support that commercial measures of objective sleep such as apps and smartwatches possess the utility for applications in research and clinical settings (Kolla, Mansukhani, & Mansukhani, 2016). Given the consistent overestimation of TST and sleep efficiency recorded through the Sleep Time app in the current study, however, clinical sleep professionals could potentially utilize the app in gathering sleep data on those suffering from sleep disorders. The Sleep Time app may offer a more accurate metric in individuals' whose sleep is extremely poor, as recording frequent sleep fragmentation throughout the night in an individual with a sleep disorder could yield a more accurate calculation of sleep time and efficiency.

### **Conclusion**

While potentially appealing to some users, smartphone technology does not provide a sensitive enough metric of common sleep variables in a healthy adult population. Future research is needed to clarify the Sleep Time app's objective measurement of sleep; that is, to investigate the amount of minutes by which the app overestimates TST for each participant, as well as the individual percentage by which the app overestimates sleep efficiency for each participant. By comparing this information to the valid measurements recorded through actigraphy, sleep professionals may be able to reliably use data recorded through the Sleep Time app. In addition, further research should look into the app's utility within clinical populations and across other models of smartphones. Likewise, objective measurement of sleep through the use of wearable movement and sleep-tracking devices should be further validated for the purpose of employing cost-efficient and expedient means of monitoring sleep in both research and clinical settings.

Validating and implementing affordable devices or applications that track one's sleep habits and patterns could create an easy way to promote sleep hygiene. In turn, this can improve the health of various populations throughout the lifespan.

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Table 1  
*Results Matrix*

	1	2	3	4	5	6	7	8	9	10	11
1. BAI total score	-										
2. BDI total score	.43*	-									
3. Age	.03	.54**	-								
4. Likelihood of future use	.07	.03	-.04	-							
5. Ease of app use	-.20	.09	-.01	.47**	-						
6. ESS total score	.31	.05	-.01	.3	.06	-					
7. Sleep quality rating	.29	.07	-.09	-.12	-.30	.45*	-				
8. FAS words total	.17	.02	-.24	-.26	-.33	-.07	-.08	-			
9. Animals total	-.17	-.40	-.43*	-.00	-.10	-.07	-.37	.61**	-		
10. LNS total	.01	.16	-.02	.09	.10	.13	-.34	.13	.13	-	
11. Total # caffeinated drinks	.04	.22	.17	.04	-.14	.15	.25	-.24	-.29	.22	-

**Note.** \*  $p < .05$ , \*\*  $p < .01$

Table 2  
*Percentage of Time App Overestimated TST & Sleep Efficiency*

<i>Participant ID</i>	<i>TST</i>	<i>Sleep Efficiency</i>
1	100%	50%
2	86%	14%
3	83%	17%
4	100%	100%
5	100%	100%
6	100%	100%
7	100%	80%
8	75%	25%
9	75%	50%
10	80%	80%
11	100%	100%
12	100%	25%
13	100%	57%
14	100%	60%
15	20%	40%
16	100%	80%
17	100%	100%
18	100%	60%
19	100%	43%

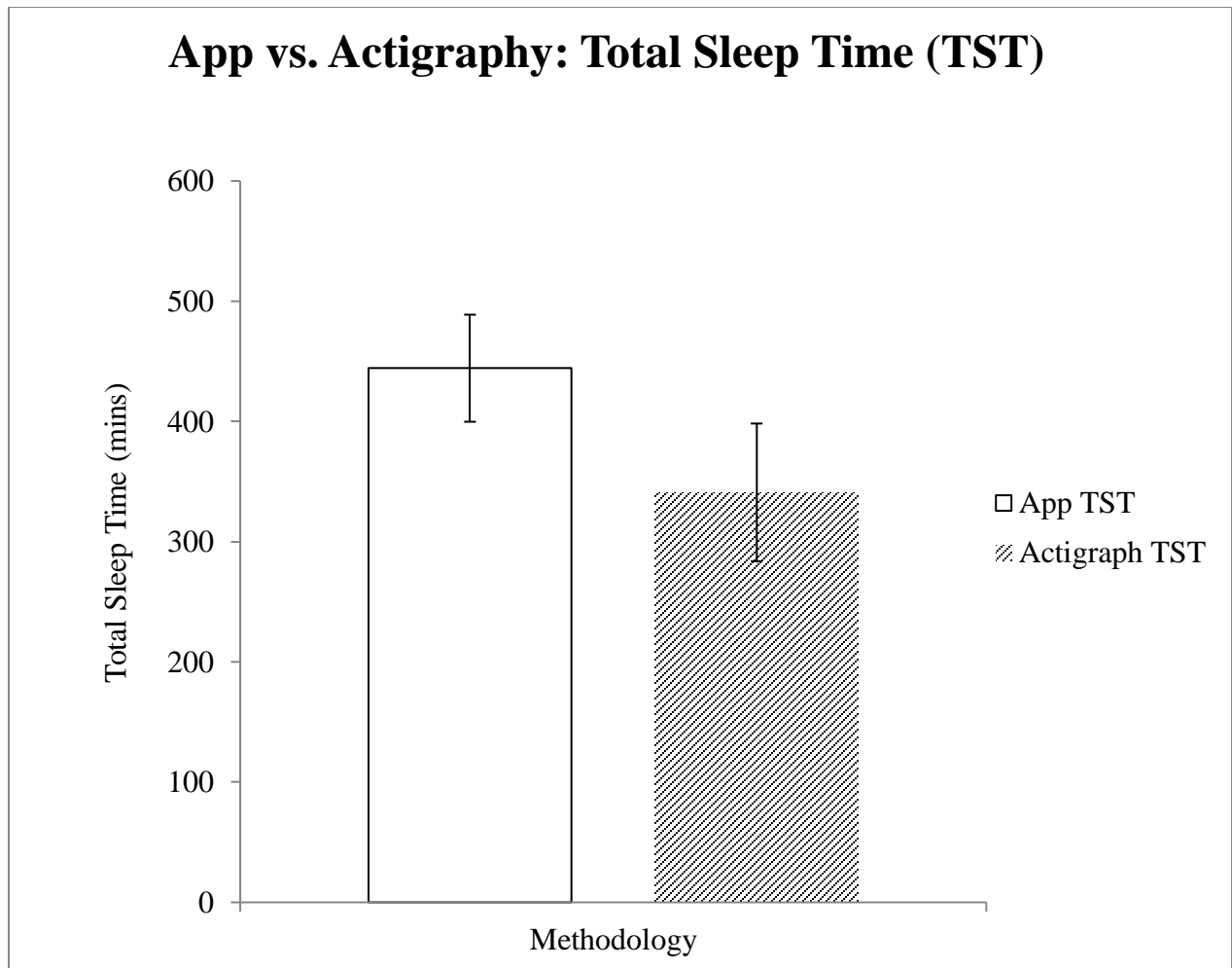
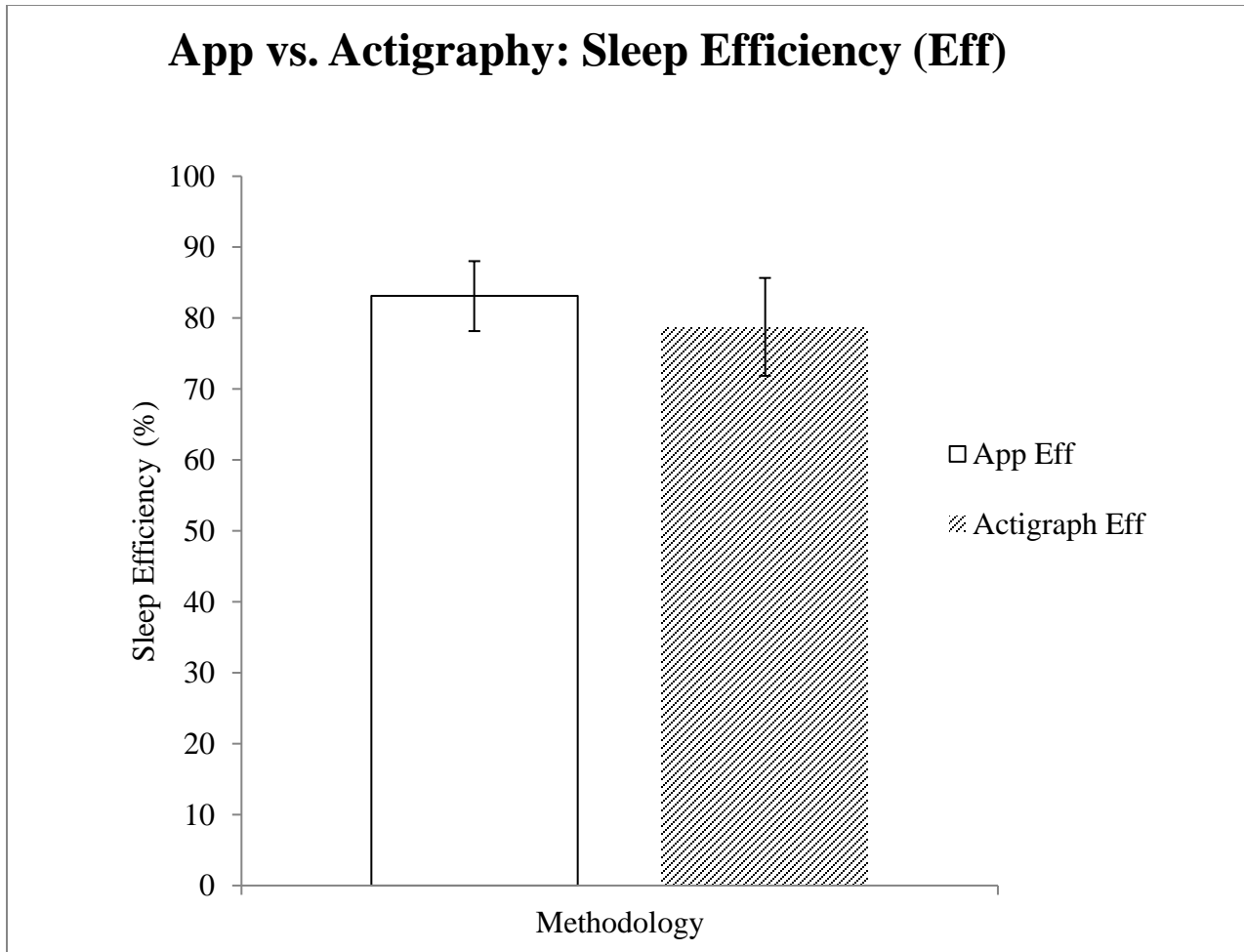


Figure 1. Graph comparing TST as measured by the Sleep Time app ( $M = 444.3$ ,  $SD = 44.52$ ) to TST measured by actigraphy ( $M = 341.0$ ,  $SD = 57.30$ ).



*Figure 2.* Graph comparing sleep efficiency as measured by the Sleep Time app ( $M = 83.1$ ,  $SD = 4.93$ ) to sleep efficiency as measured by actigraphy ( $M = 78.8$ ,  $SD = 6.90$ ).



## Appendix A

**Participant Information Form (Screening)**

- 1.) ID number: \_\_\_\_\_
- 2.) Gender: \_\_\_\_\_
- 3.) Date of Birth: \_\_\_\_\_
- 4.) Handedness: \_\_\_\_\_
  
- 5.) Are you a BU student?
  - a. Yes
  - b. No

**\*IF YES, Are you a current student of Professor Alice Cronin-Golomb?**

  - a. Yes
  - b. No

**\*IF YES, PARTICIPANT IS INELIGIBLE**
  
- 6.) Do you have a diagnosed sleep disorder?
  - a. Yes
  - b. No

**\*IF YES, PARTICIPANT IS INELIGIBLE**
  
- 7.) Are you taking any prescription or over the counter sleep aids?
  - a. Yes
  - b. No

**\*IF YES, PARTICIPANT IS INELIGIBLE**
  
- 8.) Do you have an iPhone?
  - a. Yes
    - i. If yes, what version? \_\_\_\_\_
  - b. No

**\*IF NO or OS version is lower than 8.0, PARTICIPANT IS INELIGIBLE**
  
- 9.) Are you able and willing to download the Sleep Time application to your iPhone?
  - a. Yes
  - b. No

**\*IF NO, PARTICIPANT IS INELIGIBLE**
  
- 10.) Are you able and willing to wear a wrist actigraph for one week on your non-dominant hand?
  - a. Yes
  - b. No

**\*IF NO, PARTICIPANT IS INELIGIBLE**