WIRELESS WEARABLE DEVICE FOR THE ACQUISITION OF BIOELECTRICAL SIGNALS FOR APPLICATIONS IN SLEEP MONITORING AND LUCID DREAM INDUCTION

A Thesis
Submitted to the Graduate Faculty
of the
North Dakota State University
of Agriculture and Applied Science

By

Andrew Shannon Nawrot

In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE

Major Program:
Biomedical Engineering

July 2021

Fargo, North Dakota

North Dakota State University
Graduate School

Title

WIRELESS WEARABLE DEVICE FOR THE ACQUISITION OF BIOELECTRICAL SIGNALS FOR APPLICATIONS IN SLEEP MONITORING AND LUCID DREAM INDUCTION

By

Andrew Shannon Nawrot

The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

SUPERVISORY COMMITTEE:

Dr Ivan T. Lima
Chair

Dr Trung Le

Dr Mark Jensen

Approved:

07/09/2021
Date

Dr Annie Tangpong
Department Chair

ABSTRACT

The American Academy of Sleep Medicine (AASM) recommends at minimum seven hours of sleep per night, which means you would expect to spend a quarter of your lifetime asleep. Acute or chronic sleep deprivation can greatly impair quality of life, and lead to serious health problems. Many smart devices have begun to incorporate sleep monitoring functionalities; however, their claims and accuracy can leave users misguided or unsatisfied. Conversely, clinical sleep monitoring equipment is often too complex or impractical for consistent use. In order to address this gap, it is necessary to create a device that is wearable and non-obstructive, with the capabilities to record high-fidelity bioelectrical signals from the regions of interest. The Wearable Sleep Monitoring System (WSMS) device is a simple, lightweight, wearable device that records bioelectrical signals from the user in real-time, with the capability to communicate wirelessly with a paired smartphone application.

ACKNOWLEDGEMENTS

I would like to begin by thanking Dr. Ivan T. Lima Jr. for the opportunity to work in his lab and study in the biomedical engineering program. His guidance and experience has greatly helped me to expand my understanding and become a better person and engineer. I am grateful to have been able to contribute to interesting projects and to be challenged to solve unfamiliar problems.

Additionally, I would like to thank Dr Trung Le for his collaboration and for graciously allowing us to use his SPACHeS lab space and equipment. His knowledge has been invaluable to informing the future directions of our project. Within Dr Le's lab, I greatly appreciate the time that Toan took to assist us, and the knowledge that I gained from her.

I would like to acknowledge my colleagues from Dr Lima's lab; Bobby, Quang, Julian, and Srilakshmi, who have always been able and willing to help. Whenever I struggle with a problem, they have always been willing to have stimulating discussions and debates until we reach the solution.

Finally, I would like to thank my parents, Mark and Lisa, who have always been supportive of everything I want to accomplish. I am only who and where I am today because of them, and I will never be able to properly express how grateful I am to have them.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASM.....American Academy of Sleep Medicine

WSMS.....Wireless Sleep Monitoring System

PSG .....Polysomnography

EEG.....Electroencephalography

EMG.....Electromyography

EOG .....Electrooculography

ECG.....Electrocardiography

SRS .....Sleep Research Society

REM.....Rapid Eye Movement

NREM.....Non-Rapid Eye Movement

MILD .....Mnemonic Induction of Lucid Dreams

tACS.....Transcranial Alternating Current Stimulation

1. INTRODUCTION

Sleep is a fact of life. At any moment in time, there will be millions of people who are in the middle of sleep, or trying to fall asleep, or struggling to wake up. There is no single action that is done more consistently by the entirety of humanity than sleeping, except if you just thought about breathing and eating. But it is for that reason that sleep is so important because it is necessary for survival and continued biological function just like breathing and eating. Furthermore, sleeping too much or too little is associated with increased adverse health conditions like hypertension, obesity, and diabetes (Paruthi, et. al, 2016). It is necessary to create an unobstructive methodology to monitor sleep so that individuals can become more informed about what is happening during the one-third of their lifetime that they are expected to be asleep.

1.1. Problem Overview

Sleep disturbances can have drastic effects on day-to-day life, including mental and physical health. If sleep is being consistently disturbed, it may be a sign of a sleep disorder such as insomnia. It may also be the case that an individual is unaware that their sleep is being disturbed. In 2013, a study was performed that compared the subjective reporting of sleep insomnia with the objective measurements by polysomnography (Castro, 2013). They found that only 15% of participants reported insomnia, while PSG measurements suggested a prevalence rate of 32%. While the PSG is considered the gold standard for sleep monitoring, it can be cumbersome and expensive, as well as requiring trained specialists to operate.

Recent developments in the combination of smart phones and wearable devices have allowed for new possibilities in sleep monitoring. Most often, sleep monitoring functionalities have been added to commercially available devices worn on the wrist, such as smart watches. These devices utilize the actimeter to detect the movement of limbs, however numerous studies

have compared the sleep monitoring results of only a wrist-worn actimeter with PSG and concluded that it is ineffective to determine sleep stages (Guillodo, 2020). Further experiments have been done using wrist actimeters in conjunction with electrocardiography (ECG) recordings, and results indicate over 70% agreement between sleep staging classified with the system compared to PSG (Muzet, 2016). The ECG recording provides additional information about the instantaneous heart rate and heart rate variability over time, which in combination with body movement information could be enough to accurately score sleep stages and stage transitions (Muzet, 2016). In the case of the previous experiment, a 12-lead ECG system was used to record the heart rate and heart rate variability, which is a major improvement over the complexity of PSG systems but may still not be satisfactory for all users. In contrast to wrist-worn activity monitors and smart watches, the PSG uses bioelectrical signals from electroencephalogram (EEG), electromyogram (EMG), and electrooculogram (EOG) to make complete hypnograms describing the sleep characteristics of the subject. While this technology and its methods are widely known and have been extensively studied, the PSG equipment itself is bulky and unsuitable for use outside of the clinic. The WSMS project proposes to use the same bioelectrical signals as the standard PSG for sleep monitoring, but packaged within a lightweight, simple, and wearable device. Bioelectrical signal recordings from the forehead have been shown to produce similar results for sleep stage scoring as traditional PSG systems (Myllymaa, 2016), while the economic and diagnostic advantages of simple wearable devices for both patient and clinician cannot be understated.

2. PHYSIOLOGY OF SLEEP

According to a joint consensus statement by the American Academy of Sleep Medicine (AASM) and the Sleep Research Society (SRS), adults should sleep for 7 or more hours per night on a regular basis (Watson, et.al., 2015). Sleeping less or more than the recommended amount is associated with weight gain, obesity, hypertension, heart disease and stroke. There is also individual variability in sleep need that is influenced by genetic, behavioral, medical, and environmental factors, and the AASM/SRS consensus notes that further investigation must be done to understand the precise biological mechanisms underlying sleep (Watson, et. al., 2015). It is currently understood that sleep/wake states are driven by complex interactions between subcortical neuromodulatory neurons in the brainstem, midbrain, basal forebrain, thalamus, hypothalamus, and cortex (Eban-Rothschild, 2018). In other words, it is likely that sleep is a distributed process that relies on synchrony between many different brain regions.

2.1. Biological Background

There are three main theories for why sleep is necessary. The first theory is that sleep is necessary to reduce the energy demands or used as a method of energy conservation. Energy savings during sleep occur through a reduced metabolic rate and reduced energy expenditure. Additionally, there exists a circadian rhythm of body temperature fluctuation, such that body temperature decreases slightly during the night. This slight decrease in body temperature during the night, which coincides with an expected decrease in the ambient temperature, could reduce the energy necessary to sustain a temperature gradient between the body and environment (Davenport, 1992). This theory is flawed by the observation that animals coming out of torpor experience a state similar to sleep deprivation (Heller, 2004). Additionally, it has been observed

that REM sleep coincides with a state of increased energy expenditure, which is the opposite from the supposed goal of energy conservation (Mignot, 2008).

The second theory on why we sleep is that sleep is necessary for facilitating information processing such as learning and memory through encouraging synaptic plasticity. It is common knowledge that cortical functions like attention and memory rapidly deteriorate during sleep deprivation. It has been proposed that learning during wake leads to the strengthening of glutamatergic synapses, the main excitatory synapse in the brain (Tononi, 2006). During sleep there is a reduction in the number of synapses such that only the most robust connections remain intact. This reduces the energy and space requirements of the learned circuits and may increase the signal-to-noise ratio for remaining connections (Mignot, 2008). While this theory may give support to show that sleep can be energy efficient, it is difficult to relate the benefits of this process for other species that do not possess the same brain structures for memory and learning.

The third theory on why we sleep is the idea of sleep as a process to restore components necessary for macromolecule biosynthesis. It has observed that a large portion of genes in the brain change their expressions during sleep, consistently across species and brain regions (Cirelli, 2004; Cirelli, 2005; Terao, 2006; Mackiewicz, 2007). These sleep-associated transcripts are largely involved in glutamatergic transmission (Maret, 2007), which may be related to synaptic plasticity at glutamatergic synapses (Mignot, 2008). Other studies have also shown that protein synthesis is increased during sleep (Ramm, 1990), specifically encoding proteins involved in the synthesis of macromolecular components and intracellular transport (Mackiewicz, 2007). Finally, *in-vivo* experiments in mice have shown increases in brain interstitial volume during sleep, corresponding to faster convective clearance of cellular activity compounds that have accumulated during wakefulness (Xie, 2013). While the theory of sleep as

a restorative process is irrespective of species or brain region, researchers doing work from both the perspective of synthesis and waste removal are still unsure if the restorative process is based on correlation or causation (Mignot, 2008).

While it is difficult to say for certain why sleep is necessary beyond the fact that we need it to survive, there may be some hints within the systems that control the regulation of sleep. There are many competing models that attempt to describe sleep regulation. The model of mutual inhibition of cholinergic and monoaminergic pontine cell groups is one proposed model (Hobson, 2000). It is known that monoaminergic and cholinergic neurons contribute to EEG waveforms seen while awake and that they reduce in activity during NREM sleep. Furthermore, research has indicated that REM sleep is associated with low aminergic activity but high cholinergic activity (Mignot, 2008).

Within the brainstem there exists a chemically specific neuromodulatory subsystem that has a differential activation in waking (noradrenergic and serotonergic systems on, cholinergic system damped) and REM sleep (noradrenergic and serotonergic systems off, cholinergic system undamped) (Hobson, 2000). McCarley and Hobson (1975) first hypothesized the reciprocal interaction model, which claimed that waking and dreaming are at opposite ends of an aminergic-cholinergic neuromodulatory continuum, with NREM sleep somewhere in the middle. This hypothesis that cholinergic mechanisms are essential for the generation of REM sleep has more recently been supported by drug-based lucid dream induction techniques explored by LaBerge. He reported higher frequencies of lucid dreaming and lucidity rates for subjects that had been given an acetylcholine esterase inhibitor class drug (LaBerge, 2004).

Other studies have identified regions of the hypothalamus that contain GABAergic sleep-promoting neurons (Saper, 2005). Based on these findings, the authors proposed a model that

defines a series of flip-flop switches in control of sleep regulation. The first switch controls the balance of sleep and waking, and it is modulated by various hypothalamic systems with preference for one side or the other. During wakefulness, monoaminergic, hypocretinergic, and cholinergic systems are active and move the switch to 'awake'. This is combated by GABAergic cells in the forebrain and hypothalamus which act to inhibit monoaminergic and cholinergic cells and move the switch to 'NREM'. Once within NREM, a second switch controls for the movement between NREM and REM sleep. Hypothalamic and basal forebrain cells continue to be active, but additional glutamatergic cells and cholinergic systems also activate to switch into REM. This re-activation of cholinergic systems is thought to generate the EEG activity in REM that is similar to wakefulness, as the systems are active in both wakefulness and REM. This model based on switches is valuable as it reinforces the need for stability, ensuring that mixed sleep/wake states cannot occur.

It is likely that sleep is a distributed process, where neuronal systems all around the brain contribute, instead of solely relying on guides from any one system. There have been different sleep-state-specific neuronal populations observed all throughout the brain (Jones, 2003), and it is likely that a combination of mutual inhibition and excitation is necessary to ensure that all state-specific systems are active at the same time (Jones, 2003; Mignot, 2008).

2.2. Sleep Stages

The American Academy of Sleep Medicine (AASM) publishes the AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications (AASM, 2007). The manual acts as the definitive reference for evaluating polysomnography (PSG) tests. It provides definitions for the stages of sleep and rules for scoring or differentiating them, including providing examples of the common features belonging to each stage. Previous to

the AASM guidelines, the original “Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects” was published in 1968 by a committee of sleep experts headed by Dr Allan Rechtschaffen and Dr Anthony Kales, the names behind the shortened R&K Manual.

According to AASM, sleep is divided into five stages: Stage W (Wakefulness), Stage N1 (NREM 1), Stage N2 (NREM 2), Stage N3 (NREM 3), and Stage R (REM). Stage W represents the waking state, which ranges from fully alert to drowsy. The main features of Stage W are the presence of alpha rhythm, an 8-13 Hz sinusoidal activity recorded in the occipital region, as well as eye blinks and reading eye movements. Stage N1 signals sleep onset and features a shift in the recording towards lower amplitude, mixed frequency (4-7 Hz) activity and slow eye movements (SEM). Stage N2 sleep expresses two prominent features, K complexes and sleep spindles. K complexes are single sharp peak and trough, often with a deflection of greater than 100 μV. They are thought to function in suppressing cortical arousals in response to external stimuli and engage in information processing related to memory consolidation (Halasz, 2005; Cash, 2009). Sleep spindles are a train of distinct waves with 11-16 Hz frequency and duration of 0.5 seconds or longer, often closely following a K complex. Although the mechanisms are not well-understood, sleep spindles appear to play a role in modulating responsiveness to external stimuli during sleep, and the consolidation of long-term memory (Luthi, 2014). Stage N3 consists of low frequency (0.5-2 Hz), high intensity (P-P >75 μV) waveforms. This stage of sleep is thought to be the most restful stage of sleep (Waterhouse, 2012). Finally, Stage R, the stage known as REM sleep and targeted specifically by most lucid dream induction techniques. According to the AASM Manual, Stage R contains rapid eye movements (REM), which are irregular, sharply peaked deflections usually lasting <500 milliseconds. Additionally, Stage R features low

amplitude, mixed frequency activity similar to Stage N1, but interspersed with trains of sharply contoured sawtooth waveforms. It is interesting to consider that as sleep has been more researched, we have taken to dividing it into the labels of REM and non-REM, despite non-REM being the larger of the two by time. Perhaps as we continue to investigate the role of sleep, we may one day change the label of awake to non-sleep.

Table 1: Overview of EEG frequencies and features present in each sleep stage.

Properties	**Stage W**	**Stage N1**	**Stage N2**	**Stage N3**	**Stage R**
EEG	Alpha >50% (8-15 Hz) Beta (16-31 Hz)	Alpha <50% (8-15 Hz) Theta (4-7 Hz) Vertex Sharp	Delta <20% (1-4 Hz) Theta >80% (4-7 Hz) K Complex Sleep Spindles	Delta >20% (1-4 Hz) Theta (4-7 Hz)	Beta (16-31 Hz) Theta (4-7 Hz) Saw Tooth
EMG	High	Medium	Low	Low	Muscle Atonia
EOG	Eye Blinks	SREM	Mirror EEG	Mirror EEG	REM

The following figures (Figures 1-7) have been created from PSG data taken from one individual over one night of sleep in Dr Trung Le's SPACHeS laboratory during a collaboration experiment. Figure 1 shows the sleep stage distribution of the whole night of sleep. Sleep stage scoring was done in accordance with AASM guidelines, which outline NREM Stages 1-3 and NREM. The idea of NREM Stage 4 sleep was outlined in the original R&K sleep staging but was fit into the other stages in the release of the AASM sleep staging guidelines. Sleep architecture (organization) outlines that there are generally 3-5 NREM-REM cycles during the night, during which Stage N3 occurs mostly during the first half of the night and Stage R occurs in longer episodes during the second half of the night. These organizational qualities can be roughly approximated from the hypnogram in Figure 2.

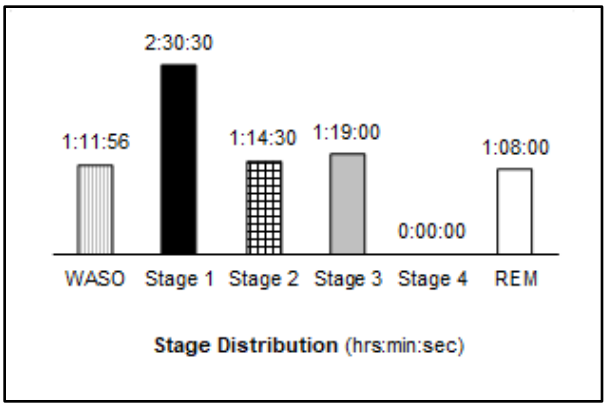

Figure 1: Sleep stage distribution from one individual over one night of sleep collected by PSG, scored by experienced technician.

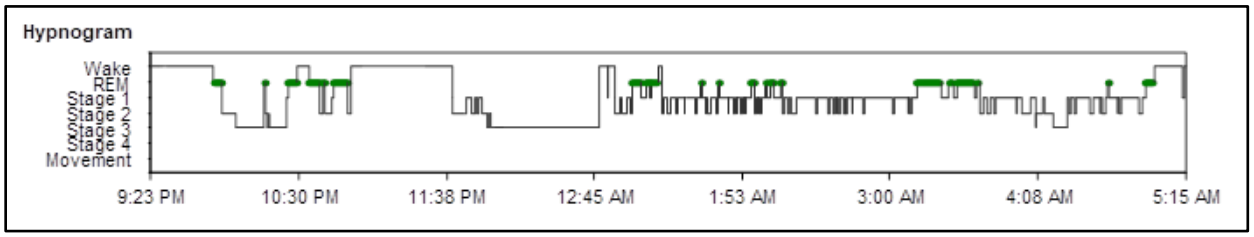

Figure 2: Whole night hypnogram from one individual over one night of sleep collected by PSG, showing the time scale distribution and movement between sleep stages.

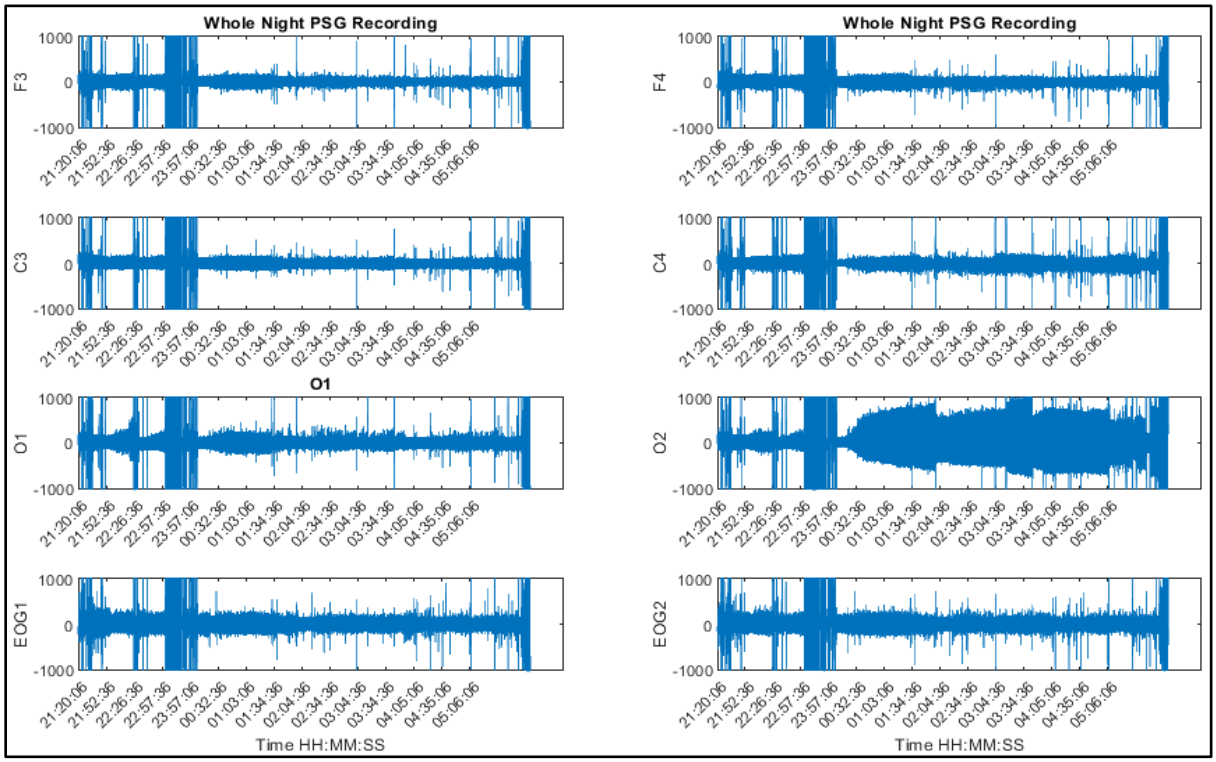

Figure 3: Plots of recorded signal at each scalp electrode site: F3, F4, C3, C4, O1, O2, EOG2, EOG2. At approximately 12:30am the electrode at site O2 was disconnected during sleep movements.

Figure 3 is the plots of the whole night of recording, divided into the signal obtained at each electrode site: F3, F4, C3, C4, O1, O2, EOG1, and EOG2. The electrode sites F, C, and O correspond to their locations in the 10-20 system of scalp electrode placements. The recordings are in reference to signal M1 or M2 taken from behind the ear on the opposite side of the head. For accurate sleep stage scoring according to AASM guidelines it is necessary to include chin EMG information, but that information was not exported as part of the data set and has not included in the plots. The PSG experiment protocol also captured information regarding chest and abdomen movement, Sa02, ECG, right and left leg EMG, airflow, and snoring vibrations, but those data were not exported as part of the data set and have not been included in the following plots.

EEG frequency features are usually divided into bands that represent the frequency of rhythmic activity present in the EEG signal. These definitions of different EEG frequency bands have been defined and refined as researchers notice certain distributions of frequency ranges over regions of the scalp or relate the bands with different biological functions. The Delta band is the lowest frequency, usually between 1 and 4 Hz. It generally has a higher amplitude than surrounding signals and occurs in sleep stages N2 and N3, usually in the frontal region. The Theta band is the second lowest frequency, usually between 4 and 7 Hz. It generally has a lower amplitude and can be found in all stages of sleep, most often in the central regions of the brain. The Alpha band is most often related to drowsiness and is found in the occipital regions during Stage N1. It has a frequency range of 8 to 15 Hz, and a medium amplitude compared to other bands. The Beta band is the highest frequency band generally measured for EEG, at 16 to 31 Hz. It is measured in the frontal and central regions of the brain with a low amplitude and indicates W or R sleep stages. Additional EEG features that do not fall rhythmic activity and are instead

classified as transient activities are the Vertex Sharp, Sleep Spindle, K Complex, and Saw Tooth waveforms. Vertex Sharp waveforms are generally found in stage N1, while Sleep Spindles and K Complexes are generally features of stage N2 sleep, and are absent in Stage R. Saw Tooth waves can be found in Stage R, however conjugate eye movements are a better indicator of Stage R.

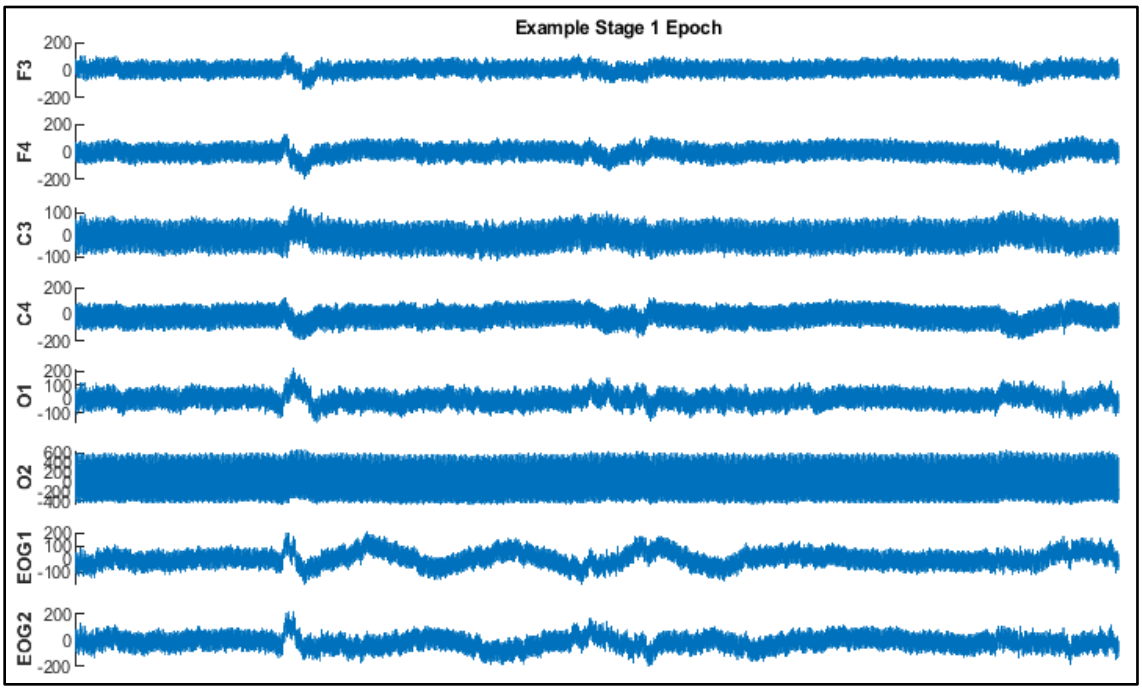

Figure 4: Example Stage N1 epoch extracted from the night of sleep data recorded by PSG.

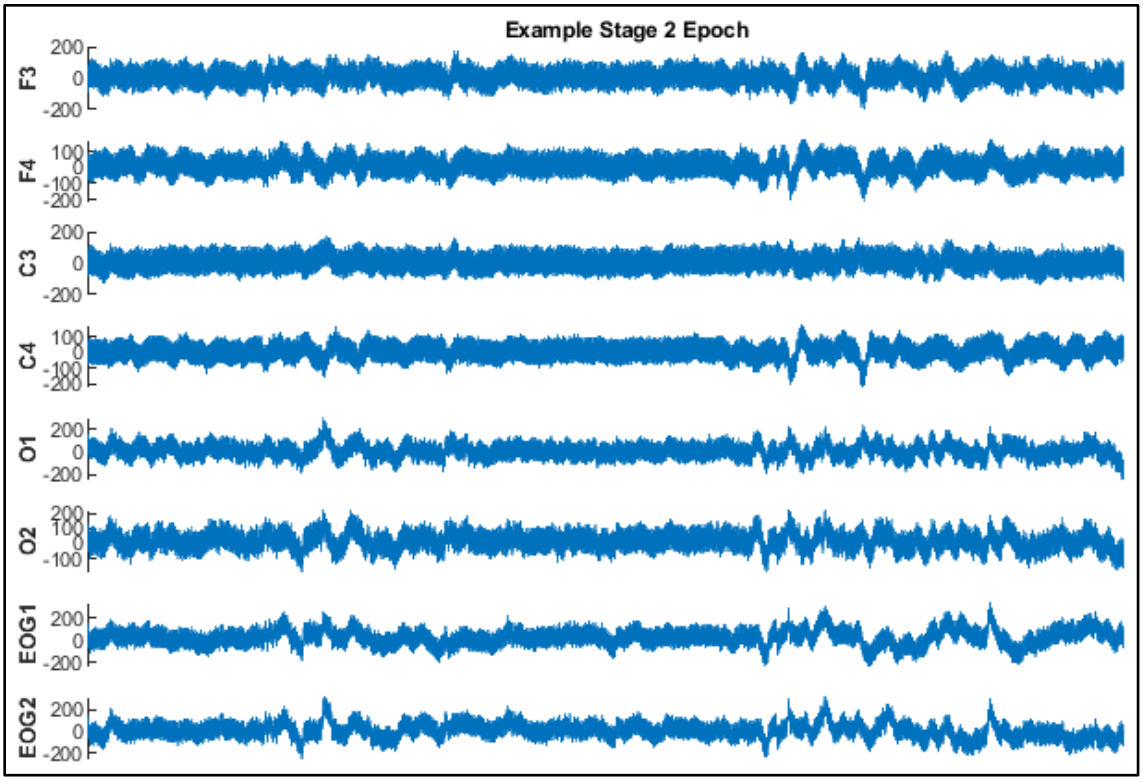

Figure 5: Example Stage N2 epoch extracted from the night of sleep data recorded by PSG.

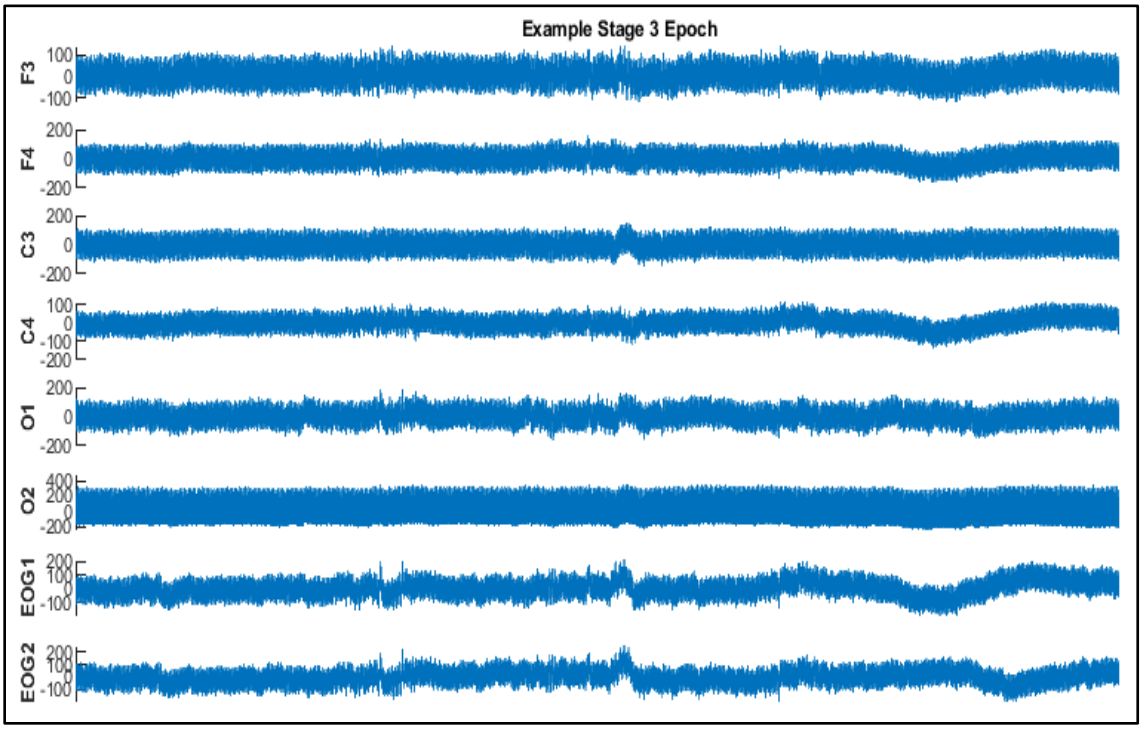

Figure 6: Example Stage N3 epoch extracted from the night of sleep data recorded by PSG.

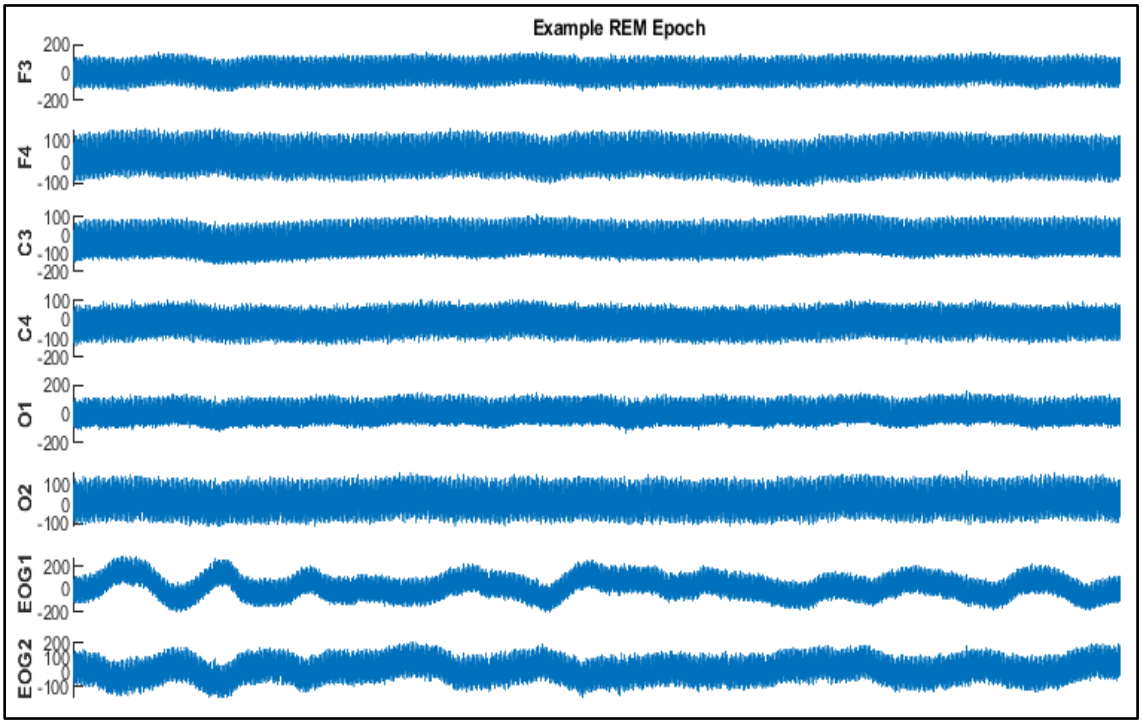

Figure 7: Example Stage R epoch extracted from the night of sleep data recorded by PSG.

3. DREAMS AND LUCID DREAMS

Definition of dreaming (Hobson, 2000):

"Mental activity occurring in sleep characterized by vivid sensorimotor imagery that is experienced as waking reality despite such distinctive cognitive features as impossibility or improbability of time, place, person and actions; emotions, especially fear, elation, and anger predominate over sadness, shame, and guilt and sometimes reach sufficient strength to cause awakening; memory for even very vivid dreams is evanescent and tends to fade quickly upon awakening unless special steps are taken to retain it."

Due to the many physiological differences between REM and NREM sleep, many researchers have been interested in exploring the dream experiences during each stage. Hobson et al (2000) reviewed over 40 years of sleep research and distilled the observations into a series of differences found between REM and NREM sleep:

1. Following awakenings from REM sleep, dream reports are obtained much more frequently than following awakenings from NREM sleep.
2. The frequency of dream recall reduces as awakenings are delayed past the end of REM sleep. Also, subjects are more likely to indicate that they are dreaming during REM sleep than during NREM sleep.
3. Dream report word count and subjective dream duration estimates are positively related to the length of preceding REM sleep.
4. Judges are able to distinguish NREM dream reports and REM dream reports, and some subjects are capable of determining if they have been awakened from REM or NREM sleep.
5. REM dream reports are generally longer, more perceptually and mechanically vivid, emotional, and less related to daily life when compared to NREM dream reports.

6. NREM dream reports generally contain more thought-like mental activity and representations of daily concerns when compared to REM dream reports.

Hobson continued by creating a series of characteristics and features that appear to be consistent throughout REM sleep dreams, but are not often found in NREM sleep dreams:

1. Dreams most often contain visual and mechanical hallucinatory perceptions, but occasionally any or all of the other sensory modalities.
2. Dream imagery can be rapidly changing and bizarre in nature, but it can also contain many images and events that are relatively banal.
3. The dreamer is constantly fooled into believing that they are awake unless they intentionally attempt to become lucid.
4. The ability to self-reflect is generally absent or reduced while dreaming, and generally relies upon weak or illogical explanations.
5. Orientational stability of people, times, and places is generally lacking in dreams.
6. Dreams attempt to contain every dream element into a singular, fluid story line.
7. Dreams contain increased and intensified emotions. The main emotions during dreams have been thought to be fear and anxiety, however further research has contested that the emotional state is balanced.
8. Dreams contain an increased incidence rate of instinctual reactions, such as the fight or flight response.
9. Volitional control is greatly diminished during dreams. This level of self-control of thoughts, feelings, and behavior is noted to be distinct from the phenomenon of lucidity within dreams.

Hobson hypothesized that the observations regarding the phenomenological differences between the consciousness states must be related to the physiological counterparts that exist within the brain. This hypothesis formed the basis of the Reciprocal Interaction model of the REM/NREM cycle.

3.1. Biological Function of Dreams

In order to explain how brain physiology may form the series of REM dream characteristics that construct dreams in REM sleep, Hobson proposed and refined an activation-synthesis model of dream construction. At its highest level, the model explains how dream consciousness results from processes of arousal impinging upon selectively facilitated, unfacilitated or input/output-blockaded forebrain structures (Hobson, 2000). It is well understood that the brainstem is an important starting place for REM sleep generation (Fraigne, 2015; Hobson, 2000). The activation-synthesis model asserts that forebrain activation occurs through the ascending arousal systems of the pontine and midbrain reticular activating systems, which include ascending cholinergic activation systems. This activation of forebrain and hypothalamic structures is thought to allow for consciousness, eye movements, and instinctual motor pattern information. This ascending activation reaches the subcortical and cortical limbic and paralimbic structures, which are responsible for relay of sensory information as well as the emotionality of dreams. The cerebellum and basal ganglia are also activated and contribute to the fictive movements common in dreams. The primary and sensory cortices are activated through the thalamic nucleus, which transmits internal and external sensory information, however the motor cortex outputs are blocked by the motor atonia present in REM sleep. Finally, the lack of executive functions and logic planning during dreams can be explained by the deactivation of the dorsolateral prefrontal cortices during sleep. It has been shown that the dorsolateral prefrontal

cortices play important roles in reasoning and memory tasks (Hobson, 2000). Importantly, it should be noted that sensory information processing in dreaming may begin at levels downstream from the primary sensory cortices (Hobson, 2000).

3.2. Lucid Dreams

Lucid dreaming is the phenomenon where a dreaming person is aware of the fact that they are dreaming, and therefore can consciously influence the contents of the dream (LaBerge, 1985). By itself, lucid dreaming is not a common occurrence, with estimates suggesting that only half of the general population have experienced a lucid dream at least once and only one out of five people have frequent lucid dreams, up to once a month (Schredl, 2011). Lucid dreams arise most often during REM sleep, but they can rarely occur during NREM sleep (Dane, 1984) or be initiated from an awake state (LaBerge, 1986). Interest in lucid dreaming comes both from its role as a recreational activity (Erlacher & Schredl, 2010; Stumbrys, 2012) and from its practical applications, such as treatment for posttraumatic stress disorder and recurrent nightmares (Harb et al., 2016; Spoormaker, 2006). As suggested by Stumbrys (2012) in their landmark review of proposed induction techniques and their evidence, the main challenge currently facing lucid dream research is the need for a reliable induction technique to increase the frequency of lucid dreams.

3.3. Techniques for Lucid Dream Induction

There are a wide variety of methods that have been implemented to try and induce lucidity. As a part of their 2012 Induction of Lucid Dreams review, Stumbrys et. al. attempted to classify the known lucid dream induction techniques into three broad categories: cognitive techniques, external stimulation, and miscellaneous techniques. This classification system has since been adopted and referenced by other research groups.

As defined by Stumbrys (2012): “cognitive techniques encompass all cognitive activities (lucid awareness training, intention, suggestion, hypnagogic techniques, etc.) that are carried out to increase the likelihood of achieving lucidity in a dream state.” It is important to note that many of the techniques listed are functionally similar; building from each other based on what was most successful. A short description of these techniques follows:

Mnemonic Induction of Lucid Dreams (MILD). MILD was the most popular cognitive technique in the 1980s, first developed by LaBerge. The technique requires the dreamer to rehearse a dream before going to sleep, setting their intent to remember to recognize that they are dreaming (LaBerge, 1980; Stumbrys, 2012). While reported to be successful in increasing the frequency of lucid dreams, LaBerge himself notes that “most people do not have the time and energy for concentration required to learn to have lucid dreams on demand by employing the mental exercises known at present” (LaBerge, 1995).

Reflection or Reality Testing. Showcased prominently in the 2010 movie *Inception*, reflection and reality testing are the techniques that would most often come to mind when a person hears of lucid dreaming. The techniques require the dreamer to question their reality throughout the day, most often by asking questions or observing a small object for possible incongruencies that could exist in a dream. Despite being featured in popular culture, scientific research has not presented clear cut results. Dane featured the technique within the Waking Instructions component of his post-hypnotic suggestion experiments but did not specifically attribute results to the technique (Dane, 1984). In two separate experiments, LaBerge (1988) suggests that reality testing is not as effective as MILD, and later suggests reality testing can be more effective than MILD (Levitan, 1989).

Intention. Intention technique is similar to MILD, however the technique requires the dreamer to put emphasis on recognizing that a dream has arisen from their intent, instead of remembering the dream that they had rehearsed (Stumbrys, 2012). In one study on nightmare treatment, the technique was featured in their 'Lucid Dream Treatment', and they reported a decrease in nightmare frequency, possibly implying an increase in lucid frequency although it was not measured in the experiments (Spoormaker, 2006).

Autosuggestion. Autosuggestion is perhaps the simplest of the cognitive methods, only requiring the dreamer to suggest to themselves to have a lucid dream. One study reported that the technique is less effective than reality testing but suggested that it would be more effective for experienced lucid dreamers (Levitan, 1989).

Tholey's Combined Technique. There are 9 components of Tholey's Combined Technique, taking what he considered to be the best parts of the reflection, intention, and autosuggestion techniques (Tholey, 1983). The technique primarily stresses the development of a critical-reflective frame of mind and requires an immense amount of focus and time throughout the day. The components include asking yourself the question "Am I dreaming" at least five to ten times a day and asking yourself the question whenever something surprising or improbable occurs or whenever you experience powerful emotions. Studies that employed Tholey's Combined Technique reported significant increases in the frequency of lucid dreams (Paulsson, 2006; Zadra, 1992), however I believe the technique suffers for the same reasons as MILD because it is too exhaustive to maintain.

Post-hypnotic Suggestion. Post-hypnotic suggestion was used in a study on 15 hypnotically susceptible individuals, and for one night there were reported lucid dreams in 14 of 15 subjects (Dane, 1984). While the results were favorable, the majority of lucid dreams were

initiated in NREM than REM sleep, indicating that technique may not be applicable to a wider audience with the same efficacy.

As defined by Stumbrys (2012): “external stimulation includes all types of stimuli (acoustic, light, electric, vibration, vestibular, brain stimulation, etc.) presented during REM sleep that can trigger dream lucidity.” The rationale behind external stimulation is that an external stimulus can be presented to a sleeping individual and successfully incorporated into an ongoing dream (Paul, 2014). A short description of the external stimulations used to induce lucid dreams follows:

Light Stimulation. Light stimulation aims to present a sleeping individual with blinking lights in hopes of the stimulus being incorporated into the dream and recognized. LaBerge used light stimulation extensively, including in his own DreamLight device (LaBerge & Levitan, 1995). While LaBerge reported very favorable results with light stimulation (1988, 1994, 1995), Paul (2014) cautions that the results were only obtained from LaBerge’s own devices and only one study was conducted in a sleep laboratory.

Acoustic Stimulation. The effectiveness of acoustic stimulation was not conclusive across studies that utilized it (Kueny, 1985; LaBerge, 1981; Ogilvie, 1983). The exact stimulus used was either a musical tone or prerecorded voice message. Laberge’s DreamLight device incorporated a chirp tone in its Reality Test button, and one subject reported that the incorrect sound in their dream had prompted them to become lucid (LaBerge, 1995). The intensity of the sound must be adapted to each user or risk being awoken during the stimulus.

Vibro-Tactile Stimulation. Tactile stimulation was used by Paul (2014) to induce three lucid dreams over 48 applications. The areas selected were the index finger, wrist, and ankle. They concluded that the area and intensity of stimulation are important criteria that must be

adjusted to the participant in order to minimize awakenings and maximize lucid dreams (Paul, 2014).

Electrical Stimulation. Electrical stimulation was used by Voss (2014) to induce lucid dreaming. Transcranial alternating current stimulation was applied across the forehead of sleeping subjects, and fronto-temporal EEG recordings were taken. They were able to observe changes in the frequency bands of the EEG which confirmed that tACS was altering REM sleep similarly to lucid dreaming (Voss, 2014). The results were disputed by Mota-Rolim (2019), as more recent research has indicated that Voss's protocol likely did not have the size of current required to directly affect neuronal circuits (Voroslakos et al., 2018).

Application of Drugs. Due to possible links between acetylcholine and REM sleep, LaBerge performed experiments with donepezil and galantamine, which are acetylcholinesterase inhibitors (LaBerge, 2004; LaBerge, 2018). The chemicals act to inhibit acetylcholinesterase, an enzyme that catalyzes the breakdown of the neurotransmitter acetylcholine. Inhibiting this reaction, in turn, increases cholinic receptor activity in the cortical regions and theoretically the frequency of lucid dreams (LaBerge, 2018).

While there have been many proposed methods to induce lucid dreaming, none of the methods, whether cognitive or based on external stimuli, have become the singular best method. Many devices based on the external stimulation principles have been brought to market or created for research. According to Stumbrys (2012), Paul (2014), and Voss (2014), the techniques with the highest efficacy at inducing lucid dreaming are MILD, Tholey's Combined technique, light stimulation, and electrical stimulation. It has been proposed that some combination of the more effective techniques may lead to more promising results for consistent lucid dream induction (Stumbrys, 2012).

4. PATENT REVIEW ON LUCID DREAM INDUCTION DEVICES

Patents are an important tool for protecting intellectual property, especially in a niche, underdeveloped market where competitors are vying to become the household name. In order to fully understand the gap in current technology, it is necessary to look at the legal disclosures for these devices, in addition to the academic disclosures. It is possible to locate the patent applications and successfully granted patents for a number of devices that have been or are currently still on the market.

While we were in the process of pursuing our own patent, it became a valuable opportunity to understand a different side of engineering and invention. On the surface a patent review may seem very similar to a literature review but understanding the complexities and nuances of legal writing is an entirely different skill from the usual academic writing. A patent application contains a summary and description of what is going to be patented, which act to support the claims of the patent. Within the patents' claims the author must list the specific features and functionalities of their device or method such that it can be differentiated from existing patents.

As an example, Patent US 2014/0221779 A1 is the patent application for iWinks LLC's device Aurora Dreamband. Patent US 2019/0070386 A1 is the patent application for the iBand device. It was granted a successful patent the following year. Patent US 2017/0304583 A1 is the patent application for the Aladdin Dreamer device. It was granted a successful patent the following year. Within each of these applications are lengthy lists of claims regarding every aspect of the device. A single claim from US 2019/0070386 looks as follows:

" 1: A sleep improvement device comprising one or more brainwave sensors for detecting brainwaves of a user, one or more body vital sensors for detecting body vitals of the

user and a control unit that is operationally connected to said one or more brainwave sensors and said one or more body vital sensors for receiving and processing brainwave signals and body vital signals, respectively, wherein the control unit is arranged for monitoring the brainwave signals and/or the body vital signals during a plurality of epochs (E) and scoring sleep stages (AW, REM, NREM1l, NREM2, NREM3) for each epoch (E), wherein the sleep improvement device is further provided with one or more stimulus emitters operationally connected to and controlled by the control unit, wherein the control unit is arranged for: initiating a sleep meditation mode when the user is awake (AW), wherein in said sleep meditation mode the control unit is arranged for controlling one or more of the one or more stimulus emitters to emit relaxing stimuli, monitoring the brainwave signals during each epoch (E), determining when the user's brainwave frequencies for at least 20 percent of one or more of the epochs (E) are within a training range of 10 to 17 Hz and then controlling one or more of the one or more stimulus emitters to emit training stimuli; and initiating a dream improvement mode when the control unit has scored one or more of the epochs (E) as a REM sleep stage (REM), wherein in said dream improvement mode the control unit is arranged for controlling one or more of the one or more stimulus emitters to emit lucid dream inducing stimuli corresponding to one or more of the training stimuli from the sleep meditation mode."

During the patent review we were able to locate a gap that is not properly addressed in the claims of any of the current competing devices. This information was submitted to the NDSU Office of Industry Engagement and Intellectual Property for consideration.

4.1. Existing Technology

Even as research interest in lucid dreaming has been waning, there have been a number of crowd-funded devices that have garnered wide-spread interest. Mota-Rolim et. al. (2019)

published a review of the 10 most popular lucid dream devices that have been/are on the market. The devices reviewed were the DreamLight, NovaDreamer, Aurora, Remee, REM-Dreamer, ZMax, Neuroon, iBand, LucidCatcher, and Aladdin (Table 1). The crowd-funded devices including Aurora, ZMax, Neuroon, and iBand all received hundreds of thousands of dollars more support than their original goals. The devices cost from $95 to over $1000, based on Amazon, eBay, and device websites. The ZMax, Remee, and iBand are the only devices that have been made available to the public, while the Neuroon, Aladdin, LucidCatcher, and others have all been continually delayed or dropped since their initial fundings. The only device with published results is the DreamLight device created by LaBerge. The majority of devices claim to have an algorithm to detect REM, however, besides Neuroon and ZMax, they do not have technical details on how the algorithms are implemented to achieve those results (Mota-Rolim, 2019).

Following the advice of Stumbrys (2012), lucid dream induction devices that aspire to have high efficacy should look to incorporate a variety of techniques, including combining cognitive techniques with external stimuli. Many of the devices on the market work using only a single lucid dream induction principle or combine the use of techniques that have not shown high levels of efficacy. According to the device functionality descriptions in their patent applications, some devices such as the Aurora Dreamband, iBand+, and Aladdin attempt to combine both external stimulation techniques with cognitive techniques. While this functionality should theoretically improve their performance, it is difficult to find user reviews and testimonials regarding the devices, possibly due to production scarcity or discontinued support.

Table 2: Comparing major lucid dream induction devices. Features of importance include the signal that is detected, what modality of external stimulation is applied, whether the device features a REM detection algorithm, if the device is currently available to purchase, and the last quoted price of the device.

Product	**Detector Signal**	**External Stimulus**	**REM Detection Algorithm**	**Currently Available**	**Price (USD)**
DreamLight	Eye Movement	Light, Acoustic	Y	N	---
NovaDreamer	Eye Movement	Light, Acoustic	Y	N	450
Aurora Dreamband	EEG	Light, Acoustic	Y	N	300
Remee	Timer	Light	N	Y	95
REM-Dreamer	Eye Movement	Light, Acoustic	Y	N	170
Hypnodyne ZMax	EEG, Eye Movement	Light, Acoustic, Vibration	Y	Y	>1000
iBand/iBand+	EEG	Light, Acoustic	Y	Y	300
Neuroon/Neuroon +	EEG, Eye Movement	Light, Vibration	Y	N	450
Aladdin	EEG	tACS	Y	N	300
LucidCatcher	EEG, Eye Movement	tACS	Y	N	350
LucidDreamer	EEG	tACS, Light, Acoustic	Y	N	---

5. THE WSMS DEVICE

The WSMS project began in 2017 as a senior design group project in the NDSU ECE Department under the advice of Dr Ivan Lima. The goal of the project was to create a wearable device capable of recording bioelectrical signals from a person's body for the goal of sleep monitoring. In its current embodiment device records a composite EEG, EOG, EMG signal from the wearer and transmits the data wirelessly to a paired smartphone application. The smartphone application is able to process the incoming data in real time and store the data for further analysis.

5.1. Bioelectrical Signal Recording

Electrical signals are generated all throughout the human body as a method of communication. Neuronal circuits communicate between each other to pass information up and down the human body, including sensory information up to the brain (afferent) and motor information down to the muscles (efferent), as well as within regions of the brain. The simplest and most non-invasive method to measure the electrical activity of the body is with surface electrodes. Two or more electrodes are used to measure the potential (voltage) difference between them, which forms the basis of the bioelectrical signal. The specific bioelectrical signal that is being recorded by the electrodes will depend on the physiology of the recording site. For example, the bioelectrical signal obtained from surface recordings on the arms or legs will be representative of the muscular activity under the skin, while surface recordings from the scalp would show the electrical activity of the cortical neurons after being attenuated by the skull. The electric potential of each bioelectrical signal detected by an electrode is dependent on many factors including the distance between the electrode and the source of the electrical activity and number of cells generating the activity. Surface recordings of large muscles under work will

show higher potentials than small muscles at rest. Similarly, scalp surface recordings will generally not be able to record activity deep within the brain, as the voltage field gradients fall off as the square of the distance. It is important to note that EEG activity can vary depending on where the recording electrodes are located on the scalp. Different EEG features and waveforms are generated by the activities of the underlying neuron groups, which can be local to specific regions of the brain. According to the AASM Manual (2007), examples of region-specific EEG activities include Stage N1 vertex sharp waves over the central region, K-complex waveforms during Stage N2 found maximally over the frontal region, or sleep spindles during Stage N2 found maximally over the central region. While EMG activity can be consciously modulated by controlling the muscle group, EEG activity will show various frequency oscillations and spatial distributions that are associated with different brain states.

For applications in sleep monitoring, the bioelectrical signals of interest that are used in polysomnography recordings are the EEG, EMG, and EOG. Some wearable sleep monitoring technologies use the accelerometer from limb movement or variability in heart rate, but they are not as effective or accurate as PSG measurements (Guillodo, 2020). The WSMS device is positioned on the forehead, and records a composite EEG, EMG, EOG signal. The EMG signal is obtained from the frontalis muscles of the forehead, which are necessary for lifting the eyebrows. During REM sleep muscle atonia is present and muscle activity is heavily reduced. The EEG signal is obtained from the synchronous neuronal activity in the frontal lobe. Forehead EEG recordings have been shown to be just as effective as traditional EEG recordings for the purposes of sleep stage scoring (Myllymaa, 2016) as well as for use in emergency EEG recordings such as determining the presence of Status Epilepticus (Muraja-Murro, 2015). Due to the three-electrode horizontal layout of the WSMS device, the EOG signal recorded is generated

by movement of the eyes either left or right. While traditional PSG systems use three EOG electrodes to record information on horizontal and vertical eye movements, this horizontal layout of electrodes on the forehead above the eyes has been proposed in similar wearable device configurations, with results indicating that the information present in left and right EOG signals is satisfactory to assist in the detection of eye movements during REM sleep (Stepnowski, 2013; Lucey, 2016). Electrically, the eye acts as a dipole where the front potential is positive and the rear potential is negative, such that as the gaze direction shifts during REM sleep there is recorded potential difference between the electrodes above each eye. Figure 8 compares the recorded signal between the EOG signal taken from above the right eye with the signal obtained from the WSMS device. The EOG channel was chosen for this visualization because the recording site is most similar to the location of the WSMS device on the forehead. The highlighted time period of low activity preceding the large awakening event was confirmed by hypnogram results to be Stage R sleep with occasion transition between Stage N2 sleep. Within the confirmed Stage R region, both the PSG recording and the WSMS recording show the expected presence of low-amplitude EEG activity and lack of EMG artifacts due to muscle atonia. The subject had an awakening event following the confirmed REM sleep and was not able to return to sleep until approximately 11:30pm. Following comparative experiments with PSG equipment, modifications were made to increase the system gain and improve data representation, as discussed in the following hardware description. No comparative experiments with PSG equipment have been performed using the improved WSMS device.

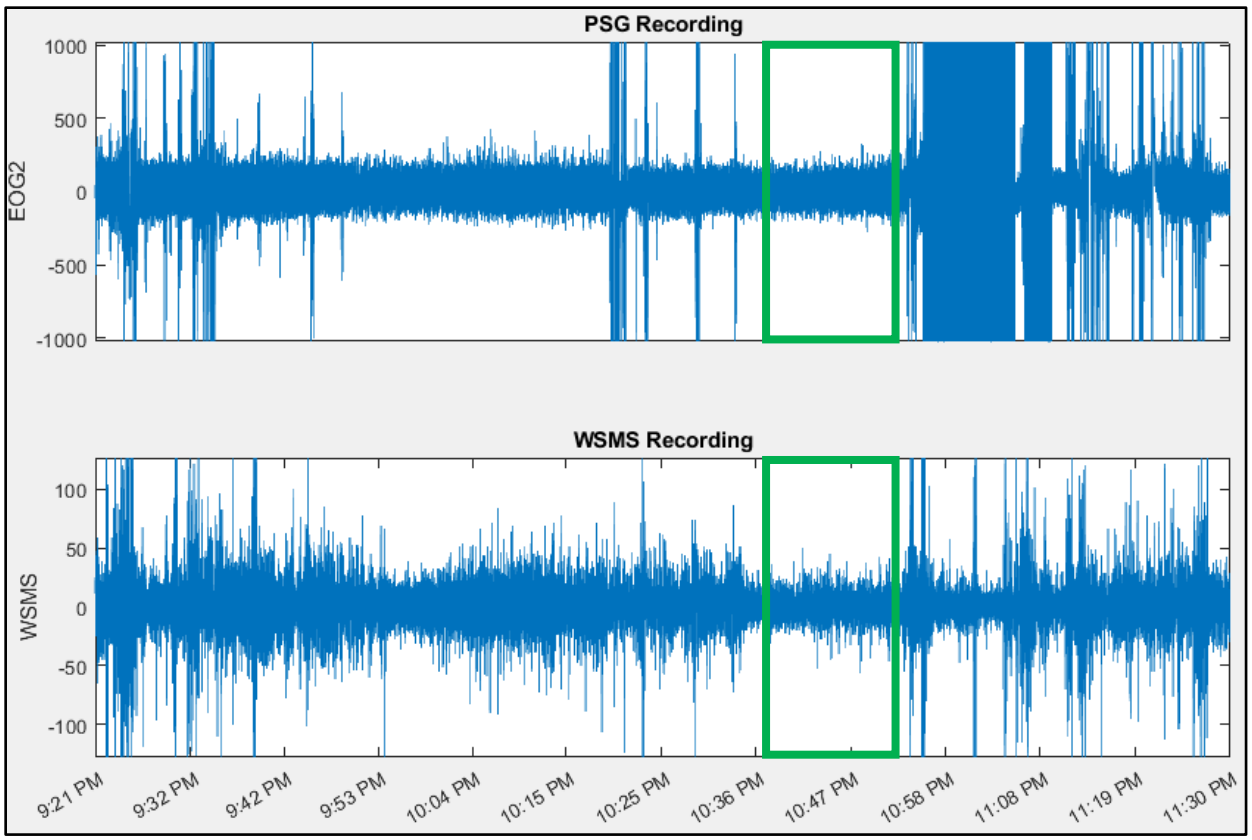

Figure 8: Comparison of recorded signals obtained from the right PSG EOG channel with the WSMS device.

5.2. Hardware and Software Description

In order to fulfill the requirements of a physically non-obstructive and easily wearable device for sleep monitoring, the recording electrode sites have been confined to the bare skin of the forehead between the hairline and eyebrows. This compromise on the physical region of the device means that while the device is unlikely to be impacted by the motions of sleep, the electrical activity that is recorded is limited to a composite signal of frontal cortex EEG, lateral EOG, and frontalis muscle EMG. In comparison, clinical PSG is able to record EEG signals from all of the left and right frontal, central, and occipital brain regions. The WSMS device features three standard dry electrode pads, which are attached to the user's forehead (Figure 8). One pad is located over each eye, with the third pad in the middle acting as the reference. Similar wearable device configurations indicate signals obtained from electrodes located only on the

forehead are able to achieve a high degree of agreement with PSG equipment for determination of sleep stage (Stepnowski, 2013; Lucey, 2016).

On the WSMS device, the signals from the electrodes are first filtered, then input into an instrumentation amplifier to amplify the difference between the signals with respect to the reference. The resulting signal is passed through low pass/gain amplifiers and a notch filter. The AASM Manual of Sleep suggests that for EEG and EOG signals of routine polysomnography (PSG) recordings, the low frequency filter be set to 0.3 Hz, and the high frequency filter be set to 35 Hz (AASM, 2007). During a gaze shift, both eyes move in the same direction such that a left gaze shift produces a positive deflection in the measured voltage, and a right gaze shift produces a negative deflection in the measured voltage. It is hypothesized that the signal recorded from the forehead contains a complex of EEG activity, EOG activity, and forehead muscle EMG activity. The strength of EEG and EOG potential is much lower than EMG, such that a 10 μV EEG signal deflection would be amplified to be noticeable within the analog to digital conversion range, while a 10 mV EMG signal deflection would saturate the range.

The signal is converted from analog to digital by an ultra-low power microcontroller in the device. The voltage range of the ADC is from 0 V to 3.3 V, with 10-bit resolution. Therefore, the expected voltage step size is 0.003 V, and the incoming signal is centered on 1.65 V to provide information regarding positive and negative voltage deflections. The AASM Manual of Sleep suggests that for EEG and EOG signals of routine PSG recordings, the sampling frequency should be set to 200 Hz at a minimum (AASM, 2007). The microcontroller transmits the digital signal to the Bluetooth low-energy (BLE) module using the onboard Universal Asynchronous Receiver/Transmitter (UART). The microcontroller is also responsible for controlling the flashing sequence of the LEDs through pulse width modulation (PWM). The Bluetooth chip then

transmits the data to the paired smartphone application. The wireless transmission is done with a maximum baud rate faster than the ADC sampling rate such that no data is lost. The 10-bit ADC output value is transmitted as three bytes: a mask with the two most significant bits, the lower eight bits, and a delimiter byte. The data is reconstructed into its integer value after it is received by the smartphone application. This is a major improvement over transmitting just one byte representing the most significant 8 bits, as the final integer reconstruction has a range of 4 times more values.

The WSMS device is housed within a 3D printed package for safety and security (Figure 9). The device is powered from a 3.7 V, 500 mAh Li-Ion rechargeable battery that allows for multiple full nights of operation between charges. The power regulation circuitry features a 3.3 V voltage regulator to ensure that the microcontroller and other active components are supplied with a voltage within their specifications. The switch to control the power is recessed in the package to minimize the chance of unintentionally turning off the device while sleeping. The battery can be recharged while connected with the device with a normal microUSB cable through the microUSB socket on the PCB, similarly, recessed into the enclosure. When the device is powered, the microcontroller will turn on one surface mounted LED that can be seen by the user, this is a simple reminder that the device is currently on.

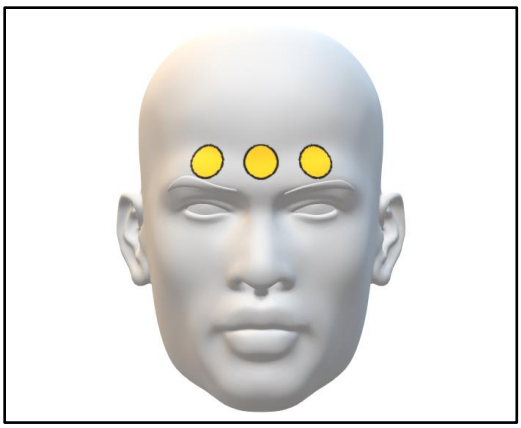

Figure 9: Location of dry electrode placement on forehead.

Figure 10: Close up view of completed device, printed enclosure, and head strap.

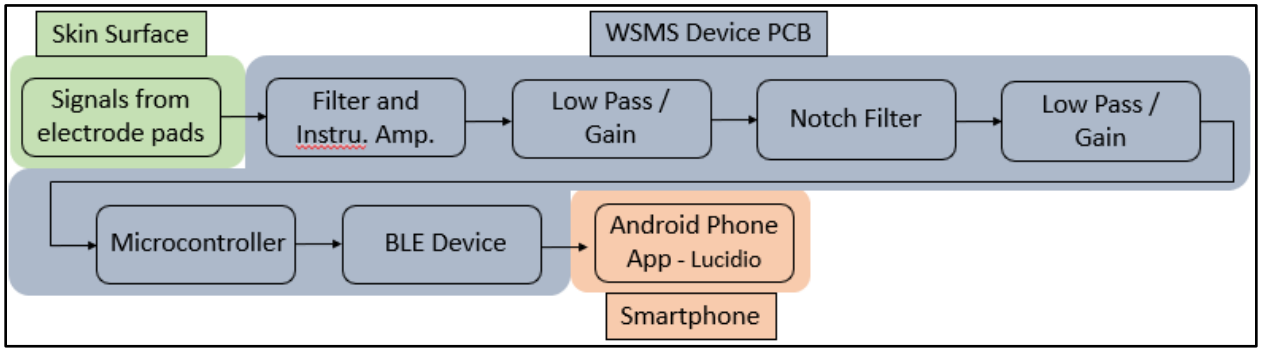

Figure 11: Block diagram description of the signal pathway from electrode to smartphone for the WSMS device.

6. APPLICATIONS OF THE TECHNOLOGY

There is growing interest in the use of wearable devices for personalized, at-home medical care. One review of the clinical applications of wearable sleep monitoring systems noted that there was an association between self-monitoring and empowerment with greater patient involvement and autonomy (Guillodo, 2020). Patients are generally more accepting of using wearable monitoring technology over frequent clinical visits, and constant monitoring generates more health information for the physician to use.

6.1. Sleep Monitoring

Most commercially available wearable sleep monitoring technology is often packaged as a secondary feature of general-purpose activity trackers. Guillodo et al (2020) concluded that one major limitation of commercially available devices is the poor accessibility of data for analysis purposes, especially for the clinical population. The authors noted that it is important that any sleep monitoring device be considered comfortable, easy to use, and preserve the natural sleep of the user. The WSMS device developed for research applications allows for complete access to the recorded data for analysis and is placed comfortably on the forehead without the need for messy wires or complicated set up.

6.2. Recording General Bioelectrical Signals

The technology developed for the WSMS project can be easily leveraged to a variety of applications. The bioelectrical signal acquisition pipeline that has been established: moving between a 10-bit analog-to-digital converter to wireless data transmission and smartphone data analysis, is not dependent on any physical component layout. The electrical circuitry can be easily modified to have specific gain and filtering characteristics depending on the bioelectrical signals of interest. The typical adult EEG signal is approximately 10-100uV when measured at

the scalp, and filters are usually configured for 0.5-1 Hz high-pass and 35-70 Hz low-pass. In comparison, average EMG potentials can range from 50 μV to 30 mV, with rates of muscle firing up to 20 Hz. In each case, the gain and filtering characteristics of the circuitry can be modified so that the signal of interest appears full-scale at the ADC input.

The physical layout of the device can be easily modified to fit the criteria for the specific signal acquisition. The electronic components can be contained within a band worn on the subject directly over the area of interest or connected through wired leads with the electrode pads and worn somewhere else.

6.3. Lucid Dream Induction

It is known that light stimuli can be successfully incorporated into dreams and trigger lucidity (LaBerge, 1995; Paul, 2014). The light stimuli presented by LaBerge was 2 flashes per second but had variable light intensity and overall duration depending on the subject's individual requirements (LaBerge, 1995). The light stimuli presented by Paul was 1 flash per second with an overall duration of 5 seconds, but no information was provided regarding the light intensity (Paul, 2014). Both experiments used red LEDs, as the red wavelength has lower attenuation through skin such as eyelids. The WSMS device similarly uses red LEDs, however the stimuli pattern can be programmed to present as any sequence imaginable. This feature of the WSMS device is because one of the main components of almost all cognitive techniques was the emphasis on recognizing queues that oneself is dreaming.

The current sequence uses Morse Code to present the dreamer with unique arrangements of stimulation such as ' . - . . - . . ', which is translated to 'LD' (for lucid dream). The user also has the ability to play the stimulus on command, in order to get into the mindset of recognizing the sequence before they go to sleep, as suggested by LaBerge's MILD technique (LaBerge,

1995). The combination of reprogrammable stimuli sequences and on-demand playback make the WSMS device more robust than comparable devices for light-based external stimulation.

7. CONCLUSION & FUTURE WORK

There are many challenges in creating wearable technology, especially for a device that is worn during a night of sleep. A person that is preparing for sleep does not want to struggle with a complicated set up procedure, and a person that is sleeping has little conscious control over possibly destructive movements if they were to toss and turn. Likewise, a medical professional would prefer to reference a long series of data in order to make the best diagnoses, but clinical sleep monitoring equipment is not conducive to extended evaluations.

In this work, I have contributed to the development of the WSMS, which is a simple, lightweight, wearable device that records bioelectrical signals from the user in real-time, with the capability to communicate wirelessly with a paired smartphone application. In order to address the needs of users, the smartphone application user interface has been improved to quickly move between the functionalities like Bluetooth connectivity, lucid dream protocol training, and WSMS sleep-mode. The sleep-mode screen shows a graph of the incoming data in real-time, as well as the possible output of a sleep stage classification and optional button to communicate back and engage features on the WSMS device. In order to improve the capabilities of data analysis, the data transmission has been modified from a singular byte transmission to a two-byte transmission, while multiple threads have been created to handle additional calculations. The data scale has been increased by four times, and the analog gain has been increased by almost five times in order to better capture small variations in EEG and EOG waveforms.

The future goals of the project include the implementation of a robust sleep stage classification algorithm within the smart phone application. As the WSMS device records and wirelessly transmits bioelectrical signals in real-time, the paired smart phone application will be working to analyze the information and determine the current sleep stage. This algorithm may be

based on work that was done to understand the RMS signal power of the signal. The recorded bioelectrical signal composed of EEG, EMG, and EOG signals contains the features of each signal. It may be possible to leverage this observation to create a classification of the stages of sleep based on the distinctive expected behavior of each signal within each sleep stage. This algorithm could be verified through comparisons with simultaneous PSG results. The smart phone application user interface can be modified to include a readout for the battery level of the device. This is accomplished through creating an additional connection between the WSMS device battery and the microcontroller ADC. Once the voltage is captured by the ADC, it can be wirelessly transmitted to the smart phone application and printed on the screen in real-time.

REFERENCES

Aserinsky, E., Kleitman, N. (1953). Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science (New York, N.Y.), 118*(3062), 273–274.

Berry, R. B., Brooks, R., Gamaldo, C. E., Harding, S. M., Marcus, C. L., B. V. (2015). The aasm manual for the scoring of sleep and associated events. Rules, Terminology and Technical Specifications (pp. 1253–1254).

Cash S.S., Halgren E., Dehghani N., et al. (2009). "Human K-Complex Represents an Isolated Cortical Down-State". *Science*. 324, (5930): 1084–87.

Castro L. S., Poyares D., Leger D., Bittencourt L., Tufik S. (2013). Objective prevalence of insomnia in the São Paulo, Brazil epidemiologic sleep study. *Ann Neurol,* 74(4), 537-546.

Dane, J. R., Van De Castle, R. L. (1984). A comparison of waking instruction and posthypnotic suggestion for lucid dream induction. *Lucidity Letter*, *3*(4).

Davenport J. (1992) Sleep, torpor and hibernation. In: *Animal Life at Low Temperature*. Springer, Dordrecht.

Erlacher, D., Schredl, M. (2010). Practicing a Motor Task in a Lucid Dream Enhances Subsequent Performance: A Pilot Study, *The Sport Psychologist, 24*(2), 157-167.

Guillodo E., Lemey C., Simonnet M., Walter M., Baca-García E., Masetti V., Moga S., Larsen M., HUGOPSY Network, Ropars J., Berrouiguet S. (2020). Clinical Applications of Mobile Health Wearable-Based Sleep Monitoring: Systematic Review. *JMIR Mhealth Uhealth, 8(4).*

Halász, P. (2005). "K-complex, a reactive EEG graphoelement of NREM sleep: an old chap in new garment". *Sleep Med. Rev*. 9 (5): 391–412.

Kueny, S. R. (1985). *An Examination Of Auditory Cueing In Rem Sleep For The Induction Of Lucid Dreams* (Order No. 8516455). Available from ProQuest Dissertations & Theses Global.

LaBerge, S. P. (1980). Lucid Dreaming as a Learnable Skill: A Case Study. *Perceptual and Motor Skills*, *51*(3_suppl2), 1039–1042.

LaBerge, S., Owens, J., Nagel, L. E., Dement, W. C. (1981). ‘‘This is a dream’’: Induction of lucid dreams by verbal suggestion during REM sleep. *Sleep Research*, 10, 150.

LaBerge, S. (1985). *Lucid Dreaming. The power of being awake and aware in your dreams.* Los Angeles: Tarcher.

LaBerge, S., Levitan, L., Dement, W. (1986). Lucid dreaming: Physiological correlates of consciousness during REM sleep. *Journal of Mind and Behavior, 7*(2-3), 251-258.

LaBerge, S. (1988). Induction of lucid dreams including the use of the Dreamlight. *Lucidity Letter, 7*(2).

LaBerge, S. P. (2004). Substances that enhance recall and lucidity during dreaming. United States patent application publication no. US 2004/0266659 A1.

LaBerge, S., LaMarca, K., Baird, B. (2018). Pre-sleep treatment with galantamine stimulates lucid dreaming: A double-blind, placebo-controlled, crossover study. *PLoS ONE, 13*(8), 1–16.

Levitan, L. (1989). A comparison of three methods of lucid dream induction. *NightLight 1*(3).

Lucey, B. P., Mcleland, J. S., Toedebusch, C. D., Boyd, J., Morris, J. C., Landsness, E. C., Yamada, K., & Holtzman, D. M. (2016). Comparison of a single-channel EEG sleep study to polysomnography. *Journal of sleep research, 25*(6), 625–635.

Lüthi, A. (2014). "Sleep Spindles: Where They Come From, What They Do". *The Neuroscientist*. 20 (3): 243–56.

Mota-Rolim, S. A., Araujo, J. F. (2013). Neurobiology and clinical implications of lucid dreaming. *Medical Hypotheses*, *81*(5), 751–756.

Mota-Rolim, S. A., Pavlou, A., Nascimento, G. C., Fontenele-Araujo, J., Ribeiro, S. (2019). Portable devices to induce lucid dreams-are they reliable? *Frontiers in Neuroscience*, *13*, 1–5.

Muzet A., Werner S., Fuchs G., Roth T., Saoud J. B., Viola A. U., Schaffhauser J. Y., Luthringer R. (2016). Assessing sleep architecture and continuity measures through the analysis of heart rate and wrist movement recordings in healthy subjects: comparison with results based on polysomnography. *Sleep Medicine*, 21, 47-56.

Ogilvie, R., Hunt, H., Kushniruk, A., Newman, J. (1983). Lucid dreams and the arousal continuum. *Lucidity Letter*, 2(2), 49.

Paruthi S, Brooks L. J., D'Ambrosio C., Hall W. A., Kotagal S., Lloyd R. M., Malow B. A., Maski K., Nichols C., Quan S. F., Rosen C. L., Troester M. M., Wise M. S. (2016). Recommended amount of sleep for pediatric populations: a consensus statement of the American Academy of Sleep Medicine. *J Clin Sleep Med, 12(6),* 785–786.

Paul, F., Schädlich, M., Erlacher, D. (2014). Lucid dream induction by visual and tactile stimulation: An exploratory sleep laboratory study. *International Journal of Dream Research, 7*(1), 61–66.

Paulsson, T., Parker, A. (2006). The Effects of a Two-Week Reflection-Intention Training Program on Lucid Dream Recall. Dreaming. 16. 22-35.

Saper C. B., Scammell T. E., Lu J. (2005). Hypothalamic regulation of sleep and circadian rhythms. *Nature, 437*, 1257-1263.

Schredl, M., Erlacher, D. (2011). Frequency of lucid dreaming in a representative German sample. *Perceptual and Motor Skills, 112*(1), 104-108.

Spoormaker, V. I., van Den Bout, J. (2006). Lucid dreaming treatment for nightmares: A pilot study. *Psychotherapy and Psychosomatics, 75*(6), 389-394.

Stepnowsky C., Levendowski D., Popovic D., Ayappa I., Rapoport D. M. (2013). Scoring accuracy of automated sleep staging from a bipolar electroocular recording compared to manual scoring by multiple raters. *Sleep Med*, 14(11), 1199-207.

Tavakoli, P., Varma, S., Campbell, K. (2018). Highly relevant stimuli may passively elicit processes associated with consciousness during the sleep onset period. *Consciousness and Cognition, 58,* (May 2017), 60–74.

Tholey, P. (1983). Techniques for Inducing and Manipulating Lucid Dreams. *Perceptual and Motor Skills*, *57*(1), 79–90.

Vöröslakos, M., Takeuchi, Y., Brinyiczki, K., Zombori, T., Oliva, A., Fernández-Ruiz, A., Kozák, G., Kincses, Z. T., Iványi, B., Buzsáki, G., Berényi, A. (2018). Direct effects of transcranial electric stimulation on brain circuits in rats and humans. *Nature communications, 9*(1), 483.

Voss, U., Holzmann, R., Hobson, A., Paulus, W., Koppehele-Gossel, J., Klimke, A., & Nitsche, M. A. (2014). Induction of self-awareness in dreams through frontal low current stimulation of gamma activity. *Nature Neuroscience, 17*(6), 810–812.

Waterhouse J., Fukuda Y., Morita T. (2012). "Daily rhythms of the sleep-wake cycle". *Journal of Physiological Anthropology*. 31: 5.

Watson N. F., Badr M. S., Belenky G., Bliwise D. L., Buxton O. M., Buysse D., Dinges D. F., Gangwisch J., Grandner M. A., Kushida C., Malhotra R. K., Martin J. L., Patel S. R., Quan S. F., Tasali E. (2015). Recommended amount of sleep for a healthy adult: a joint consensus statement of the American Academy of Sleep Medicine and Sleep Research Society. *SLEEP, 38(6),* 843–844.

Xie, L., Kang, H., Xu, Q., Chen, M. J., Liao, Y., Thiyagarajan, M., Nedergaard, M. (2013). Sleep Drives Metabolite Clearance from the Adult Brain. *Science, 342(6156),* 373-377.

Zadra, A. L., Donderi, D. C., Pihl, R. O. (1992). Efficacy of lucid dream induction for lucid and non lucid dreamers. *Dreaming, 2*(2), 85–97.