Effects of Broadband Noise on Sleep Quality

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To my beloved parents, whose boundless love and tremendous support led me to this wonderful accomplishment

To the incredible women, who empower themselves and others, inspiring me every day to strive for excellence

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dB	Decibels
std	Standard Deviation
St. Mary	Saint Mary Questionnaire
rMEQ	reduced Morningness Eveningness Questionnaire
EEG	Electroencephalography
nREM	non Rapid Eye Movement
REM	Rapid Eye Movement
PVT	Psychomotor Vigilance Task
PSQI	Pittsburgh Sleep Quality Index
AASP	Adult/Adolescent Sensory Profile

Abstract

Quality sleep is related to multiple valued performances in human life, including maintaining health and improving outcomes at work. Disturbance of sleep can increase the morbidity rate and can create multiple psychological and physiological issues. Broadband noises were hypothesized to mask disruptive noises and improve sleep quality. However, the efficacy of noise in improving sleep measures remained unclear due to the smaller sample size, uncontrolled noise environment, and sleep duration. The main aim of the study was to quantify sleep quality, sleep fragmentation, sleep latency, and relevant sleep factors by providing broadband noises and to assess whether white noise could be a non-pharmacological treatment for better sleep quality. For that purpose, sleep monitoring devices i.e., Fitbit Charge 4 and 5 as well as multiple questionnaires including PSQI, rMEQ, AASP, and St Mary questionnaire were used for data collection. Both hardware and questionnaire data were used to evaluate the effect of white noise on all the sleep factors i.e., sleep stages, sleep latency, total sleep duration, and overall sleep score. Also, environmental noise was measured by using decibel meters. Mostly healthy participants having the age of 25.07+/-4.66 for the questionnaire-based study and 24.25+/- 2.57 for hardware-based data were selected for data collection. Multiple statistical tests were performed on the collected data. ANOVA tests were performed on Fitbit's data along with the post-hoc tests. Also, chi-square tests were conducted on questionnaire data. The p-value>0.0.5 in all tests suggested that no significant effect of white noise on sleep quality. The results concluded that white noise does not play a significant role in improving sleep quality. However, it can be used as a placebo effect for better sleep for specific persons. The results are based on both sleep monitoring devices and questionnaires with proper statistical analysis, having greater sample size and under controlled environmental noise. However, this work can be extended by changing the population of the experiment i.e., infants and ICU patients to check the effects of white noise.

Keywords: Sleep, Broadband Noise, Sleep Monitoring Device, Sleep Quality, Sleep Duration

Chapter 1: INTRODUCTION

1.1 Sleep

Sleeping is an extremely complicated process that involves more than just closing your eyes and counting sheep. Sleep is a regular, reversible state of reduced receptivity to external stimuli associated with complicated, predictable physiological changes. These changes include hormonal fluctuations, muscle relaxation, and internally generated, coordinated, and spontaneous brain activity [1]. This is a physiologically determined active state of unconsciousness in which the brain is largely at rest and reacts to internal stimulus [2]. The specific purpose of sleep remains largely unclear. The brain has been the subject of many well-known ideas that have attempted to explain why people sleep. These hypotheses include the brain plasticity hypothesis, energy conservation theory, recovery theory, and inactivity theory. These hypotheses serve to formulate the idea that one does not yet fully understand sleep; They are neither comprehensive nor all-encompassing of popular ideas. It is increasingly recognized that no hypothesis can fully explain everything and that the mystery of sleep lies in a combination of these ideas [3] [4].

1.2 Functions of sleep

Sleep is a naturally occurring physiological state characterized by altered consciousness and reduced responsiveness to the environment. During sleep, there is a temporary suspension of wakeful awareness, accompanied by changes in brain activity, bodily functions, and behavior. It is a cyclical process that unfolds in distinct stages, involving shifts in brain waves, eye movement patterns, and other physiological markers. Sleep serves essential functions, including physical and mental restoration, memory consolidation, emotional regulation, and overall cognitive well-being. While the exact mechanisms and purposes of sleep are still under investigation, it remains an integral part of human life, contributing to various aspects of health, performance, and overall functioning.

Sleep serves a multifaceted range of functions that are essential for overall well-being and optimal human functioning. One of its primary roles is the facilitation of physical restoration and recovery. During sleep, the body undergoes processes that contribute to tissue repair, muscle growth, and immune system support, ensuring the body's vitality for the demands of the waking hours. Depending on the particulars of learning and the timing of sleep, sleep has been found to optimize the consolidation of recently learned information in memory.

Sleep induces changes in memory representations that are both quantitative and qualitative [5]. This process enhances learning and the retention of knowledge, thereby contributing to cognitive growth. In parallel, sleep promotes cognitive processing and problem-solving capabilities, as the brain reorganizes information acquired during wakefulness, leading to improved decision-making and creative thinking

Behavioral and physical studies show that sleep deprivation causes affective dysregulation, which in turn affects the processing of emotions and can sometimes manifest as decreased response, increased reactivity, negative bias, or the interpretation of neutral content as emotional. Emotional regulation is another significant function of sleep, particularly during REM sleep, when the brain processes and synthesizes emotions. This enables individuals to cope with daily stressors and maintain emotional resilience. Sleep also supports brain detoxification through the glymphatic system, which helps eliminate waste products and toxins, contributing to sustained brain health. Metabolic balance is intricately linked to sleep, influencing processes such as glucose regulation, appetite control, and hormonal equilibrium [6]

Evidence and interest in the significant impact of sleep loss and disorders on metabolism is increasing. Studies have clearly shown that lack of sleep can change the way the body uses glucose and the hormones that control metabolism i.e., lower levels of leptin and higher levels of ghrelin[7]. Adequate sleep is crucial in maintaining a healthy weight and reducing the risk of metabolic disorders. The immune system finds a steadfast ally in sleep, which supports the production of immune cells and cytokines that fight against infections and illnesses. Sleep deprivation weakens the immune response, leaving the body vulnerable to health challenges[8].

Furthermore, sleep contributes to cardiovascular health by allowing the cardiovascular system to rest and recover during sleep-induced decreases in blood pressure. Sleep is essential to almost all areas of physical health because it gives the body the time it needs to repair and rejuvenate. Inadequate or interrupted sleep can worsen blood pressure and increase the risk of heart disease, heart attacks, diabetes and cardiovascular system strokes. Finally, sleep is integral to maintaining a delicate equilibrium in the body's intricate systems, ensuring holistic health and facilitating the body's ability to adapt to the demands of daily life[9].

1.3 Stages of sleep

The human sleep cycle consists of two fundamental phases i.e., rapid eye movement (REM) sleep and non-rapid eye movement (NREM) sleep, which is further partitioned into three distinct stages. In total, sleep divides among five stages: wakefulness, N1, N2, N3, and REM. The N1 to N3 stages constitute the NREM sleep, characterized by an incremental progression towards deeper sleep. About 75% of the sleep duration is allocated to NREM stages, predominantly spent within the N2 stage[10]. A typical night's rest unfolds through four to five sleep cycles, featuring a sequence of stages in the order of N1, N2, N3, N2, and REM [11]. Each complete sleep cycle occupies approximately 90 to 110 minutes. The initial REM phase is brief, and as the night advances, longer periods of REM and decreased time in deep sleep (NREM) occurs.

In each phase and stage of sleep, there are differences in muscle tone, brain wave patterns, and eye movements. REM is characterized by rapid eye movements, while NREM is characterized by the absence of eye movements. The body goes through all of these phases four to six times each night, with an interval of ninety minutes between each cycle. However, gender differences also exist. Men are more likely to complain of daytime sleepiness because they usually wake up at night and spend longer periods in stage N1 sleep. Women tend to complain more often about problems falling asleep and stay in deep sleep longer than men [12].

1.3.1 Wake/Alert

EEG recording: Alpha waves are observed in the calm or relaxed waking state, while beta waves have the highest frequency and lowest amplitude.

When someone is fully awake and conscious, they are in this state. Depending on whether the eyes are open or closed, this is the initial stage or stage W. Muscle activity is evident and beta waves dominate during wakefulness with the eyes open. Humans are aware of their surroundings and recognize when they are awake. Alpha waves begin to dominate when people become sleepy and close their eyes[13].

1.3.2 N1 (Stage 1) - Light Sleep (5%)

EEG recording: theta waves - low voltage

This is the lightest stage of sleep, which starts when low-amplitude mixed frequency (LAMF) activity replaces more than 50% of alpha waves. The skeletal muscles have tone, and respiration is generally regular. This stage, which makes up 5% of the overall sleep duration, lasts for one to five minutes.

1.3.3 N2 (Stage 2) - Deeper Sleep (45%)

EEG recording: sleep spindles and K complexes

At this stage, your body temperature and heart rate decrease, signifying deeper sleep. The existence of K-complexes, sleep spindles, or both is indicative of it. Sleep spindles are short-lived, intense spikes in neuronal activity in the thalamus, anterior cingulate, insular cortices, and superior temporal gyri that cause calcium to enter cortical pyramidal cells. It has been suggested that this process is essential to synaptic plasticity. Several studies indicate that sleep spindles are crucial for the consolidation of memory, particularly declarative and procedural memory[14].

K-complexes are the longest and most recognizable brain waves. They are long delta waves that last for around a second. It has been demonstrated that K-complexes support memory consolidation and sleep[15]. The first cycle of stage 2 sleep lasts roughly 25 minutes, and it gets longer with each subsequent cycle until it makes up approximately 45 percent of all sleep. It is during this phase of sleep that bruxism, or teeth grinding, happens.

1.3.4 N3 (Stage 3) - Deepest Non-REM Sleep (25%)

EEG recording: delta waves - lowest frequency, highest amplitude

Another term for N3 is slow wave sleep (SWS). These signals, known as delta waves, have significantly lower frequencies and higher amplitudes and indicate the deepest state of sleep. This is the phase from which it is most difficult to wake up, and some people are not even woken by loud noises (over 100 dB). As people age, they often spend more time in stage N2 sleep and less time in this inefficient delta wave sleep. Although the arousal threshold is highest during this phase, someone who is awakened during this phase will experience sleep inertia, a brief period of mental disorientation. According to cognitive testing, people who awaken during this stage typically experience modest impairments in their mental function for a half-hour to an hour [16]. During this phase, the body creates bone and muscle, heals and regenerates damaged tissues, and fortifies the immune system. Additionally, this is the stage where bedwetting, night terrors, and sleepwalking happen [17].

1.3.5 REM (25%)

EEG recording: beta waves - similar to brain waves during wakefulness

REM has been considered not to be a peaceful sleep state; instead, it is connected to dreaming. The skeletal muscles are atonic and immobile, except the eyes and diaphragmatic breathing muscles, which are still working, even if the EEG is comparable to that of an awake person. But the rate of breathing gets increasingly uneven and irregular. Each REM cycle lasts longer during this period, which typically begins 90 minutes after you go to sleep. Usually, the first period lasts 10 minutes, and the last one might last up to an hour [18]. Dreaming, nightmares, and penile/clitoral tumescence all take place during REM sleep.

1.4 How poor sleep quality does affect?

Sleep is of great significance to people's mental and physical health. The quality of sleep is closely related to human growth, development, and longevity[19]. Sleep is a physiological state that is necessary for living organisms to recover normally. Normal sleep promotes health, by serving several different functions, such as clearance of metabolic waste products, neural maturation, learning, memory consolidation, restorative processes, and repair and growth throughout the brain and body[20]. However, with the acceleration of people's pace of life and the increase of work pressure, people's mental burden is also increasing, resulting in the decline of sleep quality, and the accompanying mental diseases are also on the rise[21]. Sleep duration, which results in inconvenience and disorder in people's quality of life.

In healthy adults, short-term consequences of sleep disruption include increased stress responsivity, somatic pain, reduced quality of life, emotional distress and mood disorders, and cognitive, memory, and performance deficits[16].

Increased sympathetic activity, and decreased cardiac parasympathetic activity, and subsequent tachycardia, cardiac arrhythmias, and hemodynamic instability are among the physiological complications of sleep disorder. Insomnia symptoms affect 35% of the population worldwide[18].

1.5 Treatments for better sleep quality

1.5.1 Medicines

Despite the fact that numerous medication treatments have already been established for insomnia and other sleep disorders, each patient's risk-benefit profile must be carefully considered.
Psychological-behavioral therapies frequently take precedence over pharmaceutical therapy[22], but despite the negative effects of these treatments, like addiction and rebound reactions, the number of persons primarily utilizing sleep-inducing medications to increase or improve sleep is continuously rising[17]. The side effects of taking sleeping pills which is the traditional way to intervene sleep mainly affect central inhibition and digestive symptoms and also cause drug dependency.

1.5.2 Therapies

There are many efficient therapies available to improve sleep quality and deal with concerns associated to insomnia. A particularly effective approach for treating insomnia is cognitive behavioral therapy (CBT-I), which aims to change thought and behavior patterns that interfere with sleep[23]. By using mindfulness-based techniques, such as Mindfulness-Based Stress Reduction (MBSR) and Mindfulness-Based Cognitive Therapy (MBCT), stress and anxiety that interfere with sleep can be reduced. People can use relaxation training methods, biofeedback, and sleep education to reduce stress and learn more about sound sleeping practices. Stimulus Control Therapy and Sleep Re- striction Therapy are two behavioral techniques that help people develop healthier sleep routines and effective sleep patterns. Light therapy provides a non-invasive treatment for people who experience circadian rhythm problems. A comprehensive approach to relaxing is fostered by using group therapy, yoga, tai chi, and acupuncture, which helps people have more restful sleep. Under the guidance of medical professionals, these therapies can be led to improve each patient's unique needs, which can result in better sleep and general health[24].

1.5.3 Devices

Numerous tools are available to improve sleep quality by addressing various issues that interfere with sleep. White noise devices produce calming background noises that hide interruptions and promote restful sleep. A variety of peaceful audio selections are avail- able on sound therapy devices to encourage relaxation. Wearing a smart sleep tracker while you sleep allows you to monitor your sleep habits, discover trends, and make the necessary corrections for better sleep[25]. Smart mattresses and sleep monitors use sensors to monitor movement, breathing, and heart rate, providing detailed information on the quality of the sleep. Alarm clocks with wake-up lights imitate a real sunrise to synchronize the circadian rhythm and gently awaken users. Wearing blue light-blocking glasses protects against the blue light emitted by devices.

A comfortable sleeping environment can be created using temperature-controlling furnishings like heated blankets or mattress toppers. Automation of lighting, temperature, and sound via smart home technologies creates the perfect environment for unwinding. Devices designed to stop snoring and sleep apnea include pillows and mouthpieces. Continuous positive airway pressure (CPAP)machines treat sleep apnea by continuously applying air pressure to keep the airways open. Weighted blankets apply light pressure on the body to promote comfort and relaxation. Essential oil diffusers for aromatherapy might help you relax before bed. Temperature, humidity, and noise levels are measured by smart home sleep environment monitors to promote relaxation. Dawn simulators imitate the sunlight to promote a calm morning[26].

Finally, guided exercises are available on relaxation and meditation applications to help you unwind before bed. Consider your tastes and needs when choosing your sleep aids, and seek professional advice. Moreover, Continuous positive airway pressure (CPAP) uses mild air pressure to keep the person's airways open while sleeping. This helps for the treatment of obstructive sleep apnea diseases. But the patient has to wear the CPAP device every time before sleeping. Oral devices are also designed to carry out the same purpose of opening airways and treat breath related issues during sleep[27].

1.5.4 Noise as a sleep aid

As a non-pharmaceutical alternative and, most of all, with technological advancements, evidence is accumulating in support of a role for broadband sound administration to mask environmental noise disturbances. Noise disturbances from sources either inside or outside the home are common sources of problems with sleep initiation and maintenance[28] [29]. Despite the lack of well-designed, randomized controlled trials, a National Sleep Foundation survey from 2012 reported that 5% of the American population already uses sound conditioners such as fans, air purifiers, vacuum cleaners, broadband (e.g., "white") noise devices in their rooms as makeshift sleep aids[30]. Broadband sound administration is based on the "auditory masking phenomenon" [31] whereby a masker (e.g., constant low-level noise) decreases the audibility of a disturbing signal (e.g., the indoor/outdoor noise). Masking occurs because the difference between the loudness of the background sound level and the disturbing signal is reduced, leading to a reduction in the bilateral auditory evoked response to the signal and an increase in the subjective arousal threshold [32] [33]. Moreover, sound administration may also affect sleep directly through the impact of the acoustic stimulus on brain electrical activity[34].

People define the sound with uniform loudness distribution in the auditory range of human ears (20hz-20000hz) as "white noise" [35]. White noise consists of a combination of constant sound frequency variations and comes from the environment, monotonous sound that can disguise all the sounds from the surrounding environment that are quite disturbing [45]. When we use white noise for medical purposes, the loudness of the sound usually does not exceed 10000 hertz [23]. The mechanism of white noise that can improve sleep quality is still unclear. Some research abroad shows that listening to white noise can improve sleep quality continuously by increasing the acoustic threshold to the maximum so that the surrounding noise is less able to stimulate the brain during sleep. Some research also shows that white noise affects the electrical activity of the brain and improves sleep quality by reducing the latency of sleep onset and triggering deeper sleep so that it can improve one's sleep architecture[36].

1.4 Problem Statement and Contribution

Life change events are directly linked with the disturbance of sleep. The disturbance in sleep patterns can lead to physiological and psychological issues. In most cases, it can increase the morbidity rate and can create multiple physical and mental disorders. Broadband noises are hypothesized to mask disruptive noises and improve sleep quality.

Broadband noise can be a non-pharmacological treatment for patients of every age group and enhance the everyday performance of a person, which comes as a result of better sleep quality. Through these broadband noises white noise tends to be mostly used noise for improving sleep quality. This may be through white noise machines or mobile phone applications. In either way, white noise can be a cost-effective method to improve sleep quality.

White noise auditory masking (defined as decreased audibility of background noise due to the presence of white noise) occurs because white noise decreases the difference between the background noise sound level and the disturbing signal sound level, which in turn reduces the bilateral auditory evoked response to the disturbing signal and increases the subjective arousal threshold[37][33]. There are two plausible hypotheses as to why white noise reduces sleep disruption. First, white noise may influence the arousal threshold by making it greater than the total increase in sound level. Second, white noise may reduce the difference between the background noise level and the disturbing signal noise level, leading to the improvement of sleep consolidation and a decline in sleep arousal, despite an elevation in the mean baseline level of sound, in addition to the white noise sound level[20]. However, the efficacy of noise to improve sleep measures remains unclear. Multiple studies have been performed to evaluate the effects of broadband noise on sleep, but due to small sample size, no statistical analysis, use of imprecise noise measurement tools and uncontrolled disruptive factors, the re- search is inconclusive. The current data have reported conflicting results regarding the effects of white noise on sleep quality [38][39]. Therefore, further research is required to estimate the effects of broadband noise on sleep.

1.5 Aims and objectives

Some studies suggest that various broadband noises are the non-pharmacological treatment for better sleep. The need is to test the ratio of improvement using reliable and large-scale data collection and analysis tools under controlled conditions. The main objectives of this research are as follows:

1. To quantify sleep quality, sleep fragmentation, sleep latency and relevant sleep factors by providing broadband noises.
2. To assess whether broadband noise can be a non-pharmacological treatment for better sleep quality.
3. To check whether white noise effects good and bad sleepers using PSQI questionnaire.
4. To check whether type of person w.r.t time of sleep (either morning or evening person) effect the quality of sleep using rMEQ questionnaire
5. To check does white noise effects or mask the environmental noise using decibel meter data.
6. To check is there any difference in person’s performance after sleeping with white noise on the basis of psychomotor vigilance task.

Unlike the previous studies, both the hardware based and questionnaire-based data with the greater sample size have been analyzed to check the effects of white noise on sleep quality.

Chapter 2: LITERATURE REVIEW

Sleep is a fundamental physiological process essential for maintaining physical and psychological well-being. It is an essential aspect of human life that significantly impacts cognitive performance, emotional state, and other health indicators. However, the quality of sleep can be affected by numerous environmental factors, including high levels of noise. Broadband or white noise, characterized by its uniform power distribution across a wide frequency range, has gained attention as a potential tool for improving sleep quality. This literature review examines the effects of broadband and more specifically white noise on sleep quality, synthesizing existing research to elucidate its mechanisms and potential implications for enhancing sleep.

There has been an increase in public consciousness regarding the significance of high-quality sleep for overall health and wellbeing in recent times. According to the findings of a survey conducted by the National Sleep Foundation, a minimum of six in ten Americans consider a cool, quiet, and dark bedroom environment to be three critical components in ensuring a restful night's sleep[40]. In an effort to enhance the sleeping environment, various technological devices and smartphone applications that claim to obfuscate disruptive sounds and promote rest have been introduced to the market. In May 2020, the so-called "white noise machine" (WNM) was one of the most popular applications, with at least 250 applications listed on Google Play for Android devices.

There are multiple hypotheses on the potential mechanisms through which WNMs may enhance sleep. Firstly, the transmitted sound possesses sleep-promoting or wake- reducing qualities that induce the brain into a state of sleep. There is some limited evidence that the sound of rain, for example, which is generally broadband in nature, is equally helpful as lullabies at facilitating sleep in youngsters [41]. Loewy and colleagues[39] observed that both lullabies and broadband sound lower heart rate and respiratory rate and increase sleep quality among preterm newborns.

The second theory is that white noise could "mask" the existence of other sounds that would otherwise impair sleep. Masking is a psychoacoustic process by which the threshold for perceiving one sound is raised by the presence of a masking sound[2] [29]. The human auditory system is still functioning when we sleep, so it could respond to signals that it deems pertinent [19]. The more loud the sound, the more likely it is that the body will react while a person is sleeping. The probability of the body responding to a noise during sleep increases with the sound pressure level of the acoustic stimulus[6], [42]. Partial masking may consequently lessen the perceived loudness of noise episodes, which may lessen noise-induced disruptions and fragmented sleep. Using white noise as a sensory controller is a third theory [30]. In other words, it might serve as a trigger for sleep that facilitates rapid and sustained rest.

The general sound produced by WNMs, AC units, fans, and other devices is commonly referred to as "white noise." Nevertheless, the sound that is really released could be classified as "white noise," "pink noise," or "broadband noise," each of which has distinct noise properties. The basic definitions are as follows:

Noise: Erratic or statistically random oscillation

Broadband noise: Noise whose power spectral density consists of a broad range of frequencies between a defined lower and upper frequency limit.

White noise: Noise whose power spectral density is essentially independent of frequency

Pink noise: Noise whose power spectral density is inversely proportional to frequency

A-weighting: Frequency filter applied to a sound signal to mimic the non-linear response of human hearing at moderate sound pressure levels (approximately 40 dB)

C-weighting: Frequency filter applied to a sound signal to mimic the non-linear response of human hearing to impulsive sound and to high sound pressure levels (approximately 80 dB)

Z-weighting: Alternatively “flat” or “linear” frequency response, corresponding to an sound signal unweighted in frequency

Decibel: Logarithmic measure of the ratio of a sound pressure to the reference sound pressure of the threshold of human hearing (20 mPa). Denoted as dB.

White noise is defined as a sound that is regarded as "hissing" and has an identical strength at every frequency f in the human hearing range, or around 20 Hz to 20,000 Hz. Because the lower frequencies are proportionately more intense than the higher frequencies, the sound has a deeper, lower quality. As an example of filtered noise, broadband noise only includes a portion of the whole auditory frequency range and, depending on the boundaries of the noise band, can sound at either a higher or lower frequency.

Impact of Broadband Noise on Sleep Architecture: Numerous studies have investigated the impact of broadband noise on sleep architecture, focusing on parameters such as sleep latency, sleep efficiency, and sleep stages. Basner et al. (2014) conducted a comprehensive meta-analysis, which revealed a consistent association between environmental noise exposure, including broadband noise, and disruptions in sleep architecture. They found that exposure to broadband noise during sleep led to increased awakenings, reduced time spent in deep sleep stages (e.g., slow-wave sleep), and overall fragmentation of sleep.

Physiological and Psychological Responses to Broadband Noise: The detrimental effects of broadband noise on sleep quality extend beyond disruptions in sleep architecture to encompass physiological and psychological responses. [43]discussed how exposure to broadband noise activates the sympathetic nervous system, leading to physiological arousal characterized by increased heart rate, blood pressure, and stress hormone secretion. Furthermore, chronic exposure to noise, including broadband noise, has been linked to adverse psychological out- comes such as irritability, mood disturbances, and decreased overall well-being[17].

Individual Differences in Vulnerability to Broadband Noise: Notably, individual differences play a crucial role in determining susceptibility to the effects of broadband noise on sleep quality. While some individuals may exhibit resilience to noise-induced sleep disturbances, others are more vulnerable, with factors such as age, gender, and pre-existing sleep disorders influencing susceptibility[36]. For instance, elderly individuals and those with insomnia have been identified as particularly susceptible to the adverse effects of broadband noise on sleep.

Mitigation Strategies and Policy Implications: Given the widespread prevalence of noise pollution and its detrimental effects on sleep quality, implementing effective mitigation strategies and policies is imperative. Sound insulation measures, urban planning strategies, and noise ordinances are among the interventions pro- posed to mitigate the impact of broadband noise on sleep[1]. Additionally, technological advancements in noise-canceling devices and adaptive soundscapes hold promise for reducing noise exposure and promoting restorative sleep environments.

Hence, broadband noise represents a significant environmental parameter that can profoundly impact sleep quality, sometimes leading to positive disruptions in sleep architecture, physiological arousal, and adverse psychological outcomes. Individual differences in susceptibility further underscore the need for tailored interventions to mitigate the effects of noise on sleep.

Moreover, creating an environment of constant noise in the bedroom may not be the best idea. It might cover up ambient noises that are important (like a baby crying or an alarm), or it might interfere with sleep itself. For instance, research on animals has demonstrated that exposure to continuous white noise can interfere with either rapid eye movement (REM) sleep or slow wave sleep [3]. If the sound is excessively loud, white noise may potentially cause hearing loss. The process underlying noise-induced hearing loss is intricate and involves the build-up of reactive oxygen species as well as the active activation of intracellular stress pathways that result in cell death [33]. Therefore, it is plausible that the auditory system, like the brain, need downtime to eliminate metabolic waste products that have accumulated during waking hours [18]. Lastly, there may be more negative health effects of white noise. In a review of white noise therapy for tinnitus sufferers, Attarha and colleagues[5] came to the conclusion that prolonged exposure could alter the structural and functional integrity of the brain and central auditory system. White noise therapy masks tinnitus instead of external sounds. Despite increasing popularity, the efficacy of continuous noise to improve objective and subjective measures of sleep remains un clear. The aim of this study was to systematically review the evidence regarding continuous noise as a non- pharmacological approach for improving sleep among human subjects.

Many researchers have employed broadband noise, encompassing white noise and other forms of broadband auditory stimuli, to assess its impact on sleep quality across various environments. This has been accomplished through the usage of multiple data collection tools and methodologies. Some researchers have used multiple questionnaires to check the effect of white noise on human quality of sleep. The questionnaires were collected from subjects after sleep in a specific environment either school, college, or home environment. Multiple questionnaires have been used to check the sleep quality after white noise interventions. Most of the researchers used the Pittsburgh Sleep Quality Index (PSQI), Consensus Sleep Diary, Stanford Sleepiness Scale (SSS) Col- icky Baby's Diary, State-Trait Anxiety Inventory, St. Mary, and other questionnaires based on the type of study. Whereas, some other researchers have used sleep monitoring devices for this purpose. These devices include an actigraph unit wristwatch set, Motionlogger Actigraph, and other smartwatches as sleep monitoring devices. How- ever, some sleep researchers rely only on the data provided by the patient's itself or his/her recordings. Based on data collection, studies from multiple researchers have been divided into two categories.

2.1 Questionnaire-based

It has been known that better sleep quality led to better physical and cognitive performances. In recent years, researchers has found that broadband noises might help the person either healthy or suffering from any disease with their sleep quality and quantity.

Some researchers tested the broadband noise intervention on healthy individuals. Eighteen healthy individuals were tested with multiple types of noise generators, environmental noise and broadband noise and tested with visual analog scale (VAS) and Stanford sleepiness scale (SSS). The results suggest that broadband noise may effective as subgroup. However, they agreed on better sleep[41]. White noise has been provided to high school students of Putri Rajawali Makassar for 30days which includes 60min rain played under controlled external factors. Results were in the favor of better sleep quality on the basis of PSQI questionnaires. But students experienced lack of sleep duration[39].

Elective general surgery patients experience a severe inpatient sleep disturbance, worse than in similarly studied ICU cohorts. This disturbance is driven primarily by nighttime awakenings. Previously, research has been done to check whether broadband or white noise effects the patients sleep quality, either has no visible effect or led them to better sleep. Researchers used White Noise of 50-60dB on 60 Coronary care patients in a hospital setting for three nights, and the PSQI Questionnaire based results suggested that white noise improved sleep quality[41]. In paper [44], white noise application was provided to patients in ICUs for three days and observed improved sleep quality, and the results were collected using a 4-point Likert scale questionnaire. Researchers also exposed function-based white noise on Operating room staff for three days with a 10days washed-off period and concluded that there is no effect of white noise-based State-Trait Anxiety Inventory [45].

The broadband noise intervention has been given to the insomnia patients by [40]. In the randomized controlled trial, researchers tested the effect of surrounding broad-band sound administration on sleep onset latency, sleep architecture, and subjective sleep quality in healthy subjects. They were exposed in random order to normal environmental noise (40.1 [1.3] dB) or to broadband sound administration uniformly distributed in the room by two speakers (46.0 [0.9] dB). Then data has been collected using Pittsburgh Sleep Quality Index(PSQI). This research concluded that broadband sound administration significantly reduced sleep onset latency by 38% compared to normal environmental noise.

Study has been done to check if playing of white noise be helpful for parents and healthcare personnel in reducing the gas pains of babies. This has been evaluated using a “Colicky Baby’s Diary” to calculate the total crying and sleeping durations of the babies. Researchers in[46], concluded on playing of white noise significantly decreased the daily crying durations ($p < .05$) and increased the sleeping durations of the colicky babies. Moreover, the effect of white noise has also been analyzed on children with autism spectrum disorder (ASD), attention deficit hyperactivity disorder (ADHD) in previous studies to check enhanced sleep quality. White noise with the specific rhythm, proper bedtime routine, and graduated extinction were provided to three children with ASD for one month (one-week follow-up), parents' reporting suggested that there was reducing sleep latency and less frequency of night awakening[47].

Exposure to continuous white noise of 75dB was provided to students with ADHD in both places at school and at night at home and researchers observed the decreased sleep latency and spontaneous night wakings on parents reporting. These results are ambiguous due to considerable risks of bias, lack of reliable data for sleep data in the homes as results based on parents' report selection, unmeasured sound levels, and time constraints[48] .

These studies have shown various results due to small sample size, uncontrolled external noise, not reliable and valid data collection tools or analysis, and results based only on questionnaires.

2.2 Hardware Based

Fewer studies used smart sleep monitoring devices to check the effect of white noise on sleep quality rather than the traditional questionnaire method. Researchers in [49] used white noise to mask high environmental noise in New York City and concluded improved sleep quality based on Consensus Sleep Diary and Motionlogger Actigraph. The researchers in[39] used white noise produced by AC sound and collected data using an actigraph unit wrist-watch set and found no significant positive effect of AC sound on sleep duration, latency, and efficiency. There were multiple restrictions of this study which includes age groups, background noises not objectively monitored, actigraphy being less sensitive to assess awakenings and arousals, and limited duration.

2.3 Comparative Analysis of Previous Research Studies

Although, white noises are hypothesized to mask disruptive noises and improve sleep quality. However, the efficacy of noise to improve sleep measures remains unclear. The above studies have been performed to evaluate the effects of broadband noise i.e., white noise on sleep, but due to the small sample size, no statistical analysis, use of imprecise noise measurement tools, and uncontrolled disruptive factors, the research is inconclusive. Therefore, further research is required to estimate the effects of broadband noise on sleep.

This conducted study merges both questionnaires and sleep monitoring devices for data collection. Also, the data has been collected data from a large number of samples in a comparatively controlled environment. The external noise has also been measured using the decibel meter to differentiate both the actual white noise and other disruptive noises. The sleep monitoring device provided the complete sleep data which included time awake, time asleep, no of awakenings, REM and non-REM stages as well.

Multiple questionnaires i.e., PSQI, Adult/Adolescent sensory profile, reduced morningness- eveningness questionnaire, and St. MARY questionnaire has also been used for further analysis of the data. In comparison with previous studies, our study design provides multiple dimensions to authenticate the results of the effects of white noise on sleep quality.

Paper	Subjects	Setting	Noise	Measurement Tool	Results
[30]	60 Patients (Age>30yrs)	Hospital	White 50-60dB	PSQI	Improved sleep quality
[49]	10 Healthy (Age=39-74yrs)	High env noise	White	Consensus Sleep Dairy, Motionlogger Actigraph	Improved sleep quality
[50]	12 Healthy (Age=16-18yrs)	Hostel	White	PSQI	Improved sleep quality
[44]	54 Patients (M Age= 40.28 yrs)	Hospital	White	4-point Likert Scale	Improved sleep quality
[37]	18 Healthy (Age=20-65)	Room	Env & Broadband	Visual Analog Scale Stanford Sleepinees Scale	May effective as subgroup
[47]	40 Gastric pain (Age= 1month)	Home	Swung, White	Colicky Baby's Diary	Increase sleep duration than swinging
[28]	3 ASD patient (Age=4-5years)	Home	White Rhythm	Parent's Reporting	Reduced sleep latency, minimize no of Awakening

[32]	3 ADHD patient (3rd-4th grade	School Home	White	Parent's Reporting	Reduced sleep latency, minimize no of awakening
[4]	48 Healthy (Age=18-25)	Home	White (AC Sound)	Actigraph unit	No significant effect
[38]	29 Healthy Staff (2-20yrs exp of work)	Operating room	Suction-based White	State-Trait Anxiety Inventory	No significant effect

Table 2.1. Summary of Studies on Noise and Sleep

Chapter 3: SUMMARY OF RESEARCH WORK

3.1 Background

Quality sleep is related to multiple valued performances in human life, including maintaining health and improving outcomes at work. The disturbance in sleep patterns can lead to physiological and psychological issues including daytime fatigue and sleepiness, emotional issues, and induce sicknesses such as heart disease, hypertension, anxiety, and depression. In most cases, it can increase the morbidity rate and can create multiple physical and mental disorders. Broadband noises are hypothesized to mask disruptive noises and improve sleep quality. However, the efficacy of noise to improve sleep measures remains unclear. Multiple studies have been performed to evaluate the effects of broadband noise on sleep, but due to small sample size, no statistical analysis, use of imprecise noise measurement tools and uncontrolled disruptive factors, the research is inconclusive. Therefore, further research is required to estimate the effects of broadband noise on sleep.

3.2 Purpose of study

Main objectives of the study are; • To assess sleep quality, quantity, and sources of sleep disturbances of a subject. • To quantify sleep quality, sleep fragmentation, sleep latency and relevant sleep factors by providing broadband noises. • To assess whether broadband noise can be a non-pharmacological treatment. The effects of white noise on sleep quality have been estimated by using multiple sleep questionnaires as well as sleep monitoring devices.

3.3 Methods

The research methodology comprises of two types of protocol design. i.e., Questionnaire- Based and Hardware-Based data. Questionnaire-based involves multiple pre-and post- study questionnaire, psychomotor vigilance task (PVT). Whereas, Hardware-Based study involve pre-and post-study questionnaire, psychomotor vigilance task (PVT) and mainly sleep monitoring device to provide information about sleep stages and other sleep factors. Participants for both studies are selected from university and home environment. The inclusive criteria comprise of both healthy people and those having sleep issues. The participants are screened based on any type of prescribed or unprescribed medication for sleep and neurological or psychiatric condition. The inclusive criteria comprise of participants who do not take any medications or therapies for sleep.

Participants having the age of 25.07+/-4.66 have been selected for questionnaire-based study and 24.25+/- 2.57 for hardware-based data. The subject provided with the multiple pre-and post-study questionnaire, and psychomotor vigilance task (PVT) for both studies. Whereas, Hardware-Based study involve sleep monitoring device to pro- vide information about sleep stages and other sleep factors along with the questionnaire and PVT task. The white noise will be provided to the subjects in both studies. For intervention, white noise of 0 dbW was generated. The signal power was kept constant for 8 hours. The white noise signal for active control condition was generated with 0 dBW for 30 min, which was reduced in intervals of 5 dbW every 3 minutes to reach

-50 dBW for smooth reduction in the amplitude/volume. The following 7 hours of active control signal had a power of -60 db. The noise provided to questionnaire-based subjects for 3 weeks and 3 nights each week. And for hardware-based subjects, it has been provided for 1 week. The condition will be different on different days i.e., no noise, white noise, sham noise.

3.4 Results

Multiple tests have been performed on the collected data. ANOVA tests have been applied to sleep monitoring device data that shows there is no significant effect of white noise on sleep quality. Similarly, chi-square tests have been performed on PSI vs AASP data and PSQI vs St. Mary data but no significant effects have been shown.

3.5 Conclusion

White noise does not play significant role in improving sleep quality. However, it can be used as a placebo effect for better sleep for some person.

Chapter 4: DESIGN AND METHODOLOGY

4.1 Participants

Participants included in the sleep study have been provided with consent form before participation. The inclusive criteria comprise of both healthy people and those having sleep issues. The participants were screened based on any type of prescribed or unprescribed medication for sleep and neurological or psychiatric condition. The inclusive criteria comprise of participants who do not take any medications or therapies for sleep. Participants having the age of 25.07+/-4.66 have been selected for questionnaire-based study and 24.25+/- 2.57 for hardware-based data. Participants for both studies are selected from university and home environment. The details of the participants are as follows:

Participants selected for both the studies were not overlapping. It was conditioned for each participant to take part in one type of study only depending on the willingness.

Details	Hardware	Questionnaire
No of subjects	27	54
Mean Age	24.25+/- 2.57	25.07+/-4.66
Gender	9M, 18F	29F, 25M

Table 4.1: Details of the participants included in sleep study

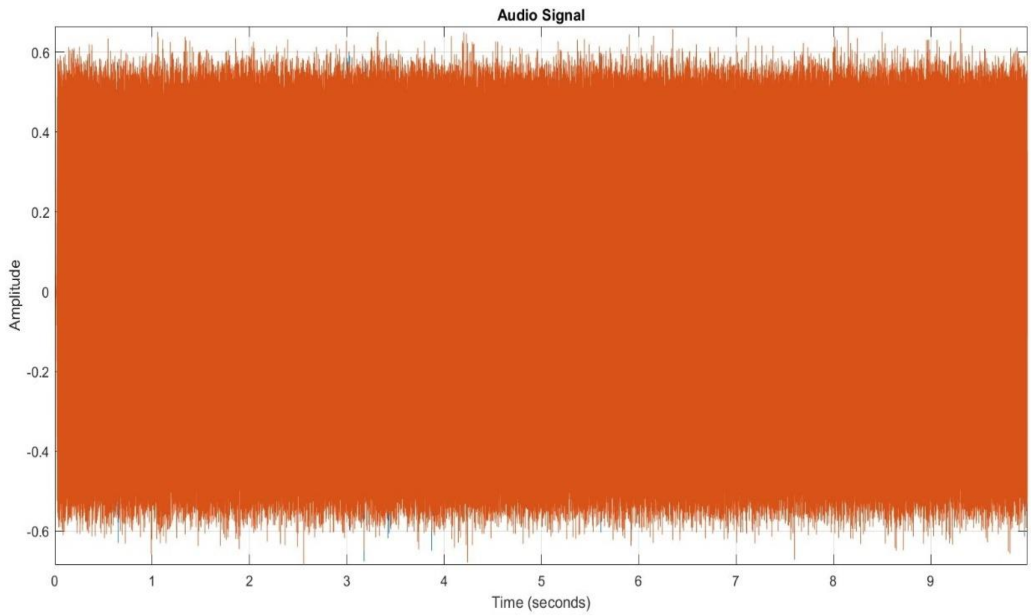
4.2 White Noise

White noise is purported to mask disruptive noises in the bedroom environment. The white noise of certain specifications has been provided to the participants. For intervention, white noise of 0 dbW was generated. The signal power was kept constant for 8 hours.

The white noise signal for active control condition was generated with 0 dBW for 30 min, which was reduced in intervals of 5 dbW every 3 minutes to reach -50 dBW for smooth reduction in the amplitude/volume. The following 7 hours of active control signal had a power of -60 dbW. An A-weighting filter was applied to both signals (intervention and active control). All the procedure was performed in MATLAB 2019b.Afterwards, the processed plain white noise has been provided to participants on the assigned intervention days. Two types of noise files have been provided to the participants.

4.2.1 White Noise

The white noise for the whole night was provided to the participants for two consecutive nights. The figure 4.1 for the white noise shows that the noise has equal amplitude for the whole night.



.Figure 4. 1: Graph of white noise provided to the subjects for whole night

4.2.2 Active Control/Sham Noise

The other white noise audio was designed in a manner to first start with its maximum peak value and then amplitude started decreases gradually. This take almost 30minutes to 1 hour to complete converted the audio signal to the silent one.

The designed white noise aimed to check the effects of white noise on sleep latency duration and to check the placebo or sham effect of the white noise on the participants. The audio file was provided to each subject for two consecutive nights to check its effects on the participants. The provided graph in figure 4.2 shows that the white noise starts from maximum amplitude and then gradually decreases to the signal where participants hear no sound or it seems like a silent audio signal.

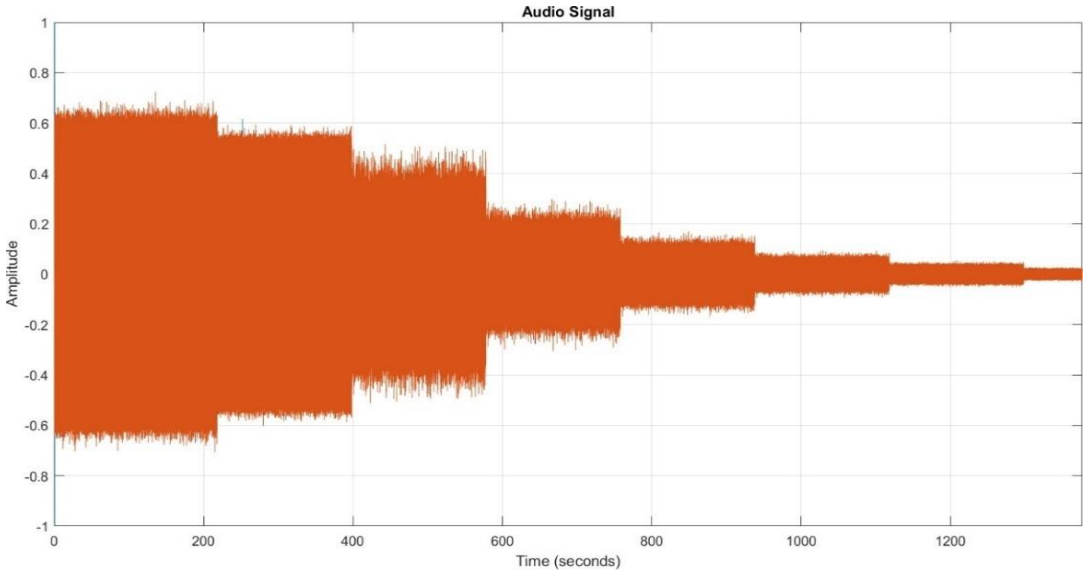


Figure 4.2: Graph of sham noise provided to the subjects for whole night

4.3 Psychomotor vigilance task

A psychomotor vigilance task (PVT task) is a sustained-attention, reaction-timed task that measures the consistency with which one responds to a visual stimulus. The Psychomotor Vigilance Test (PVT) is a widely used behavioral attention measure, with the 10-min (PVT-10) and 3-min (PVT-3) as two commonly used versions[21]. We have used PVT-3 (i.e., 3min task) to measure the attention time of the participants the next day with or without white noise intervention. The task was performed before filling out the pre- and post-study questionnaires. The PVT task shown in figure 4.3 was designed in a way that the numbers i.e., delayed time pop up on the screen one has to click the number this will measure your alertness associated with sleep factors. The collected data is then downloaded in Excel format and then processed for analysis.

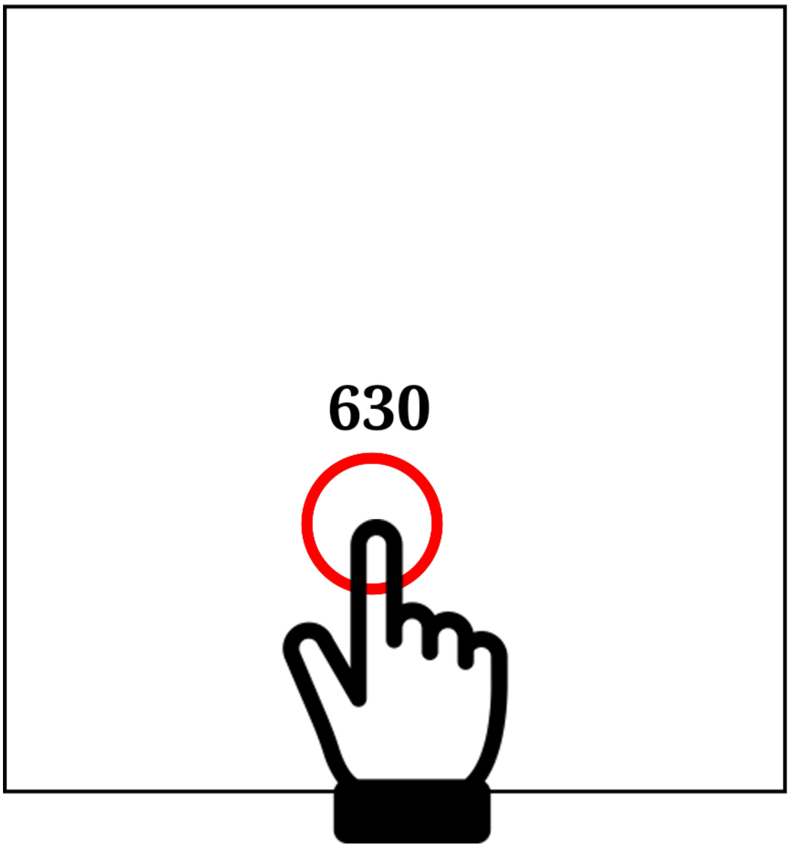


Figure 4.3: Screen of pvt task used to measure attention-reaction time of subjects

4.4 Sleep monitoring Device

Sleep monitoring has been performed using smart watches Fitbit Charge 4 and 5 (Fitbit Inc). The purpose of using this device is that it provides comparatively more accurate sleep data than other smartwatches. Human's sleep follows sleep architecture because sleep has a biological rhythm. The International Society of Sleep Medicine classifies sleep into two phases of sleep, (1) rapid eye movement (REM) and (2) non-rapid eye movement (NREM) sleep, which is further divided into three stages, N1-N3. Each phase and stage of sleep includes variations in muscle tone, brain wave patterns, and eye movements. The body cycles through all of these stages approximately 4 to 6 times each night, averaging 90 minutes for each cycle.

The Fitbit uses a combination of movement and heart rate metrics to help determine sleep patterns and estimate sleep stages which include light, deep, and REM stages. Movement metrics have been measured by built-in accelerometers of Fitbit which can indicate when one can toss and turn or get out of bed during the night.

Heart rate has been used to estimate when a person moves from one sleep stage to the next. Heart rate data and activity data were collected using Fitbit Charge 4 and 5 (Fitbit Inc). Participants were asked to wear the device on their non-dominant hand before sleep each night for five consecutive days. The collected data included information on how long the participant slept, how much body movement occurred during sleep, when the participant woke up throughout the night which includes the number of awakenings as well, and the estimated time a participant spent in each sleep stage. The collected data has been exported in an Excel file for further processing.

Figure 4.4 has shown the Fitbit data using the Fitbit mobile application it provides the sleep related parameters including time asleep, time awake, total awake time, total sleep time, sleep stages i.e., Light, Deep and REM sleep duration in minutes. The restoration percentage has also been provided by the sleep monitoring device which includes sleep heart rate and restlessness.

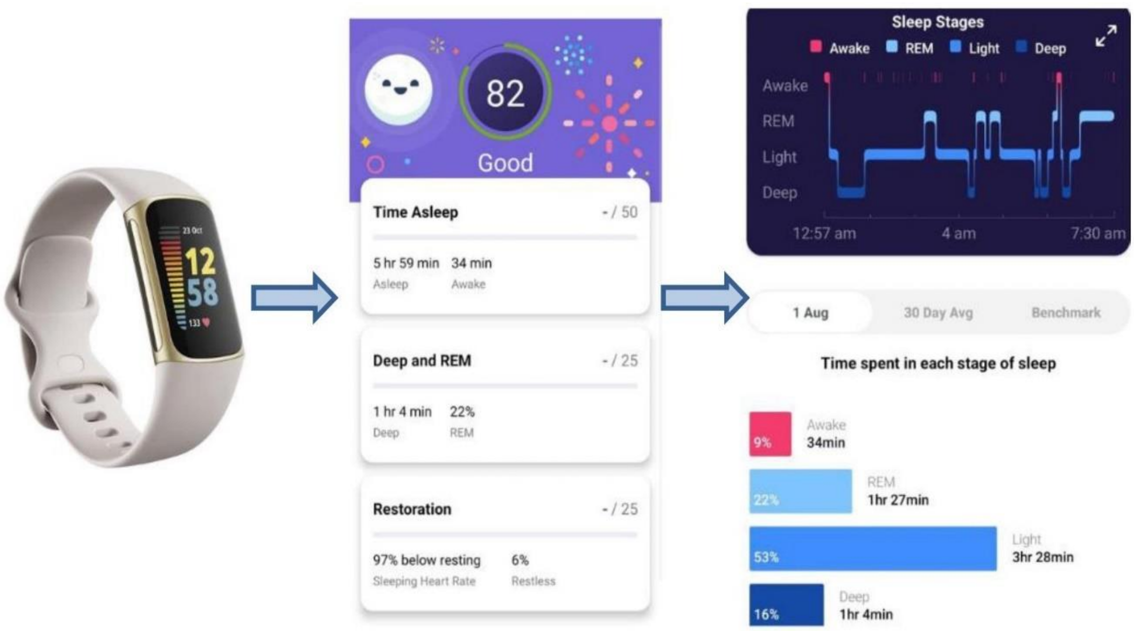


Figure 4. 4: Fitbit watch sleep data after syncing with Fitbit mobile application

4.5 Decibel meter

The decibel meter has also been used to measure the environmental noise. This Digital Sound Noise Level Meter or decibel meter is majorly used to meet the measurement requirement of safety engineers, health, industrial safety offices and sound quality control in various environments, which include factory, office, traffic, family and audio system. In this project, the decibel meter has been used to measure the environmental noise in the data collection area which is either home or university hostile environment.

In this project, Benetech GM1356 has been used which is designed according to the IEC PUB 651 TYPE 2 and ANSI S1.4 TYPE 2. The instrument has an accuracy level up to +/- 1.5 dB within the measurement range of 30 - 130 dB. The decibel meter provides both AC and PWM signal output. But the AC output has been collected to visualize the signal output. Table 4.2 shows some specifications of the digital sound level meter on the basis of which the calibration was done.

Figure 4.5: Decibel meter used for measuring environmental noises

Specifications	**Calibration**
Measuring Range	30 - 130 dBA; 35 - 130 dBC
Accuracy	±1.5 dB (reference sound pressure standard, 94dB@1KHz)
Frequency Range	31.5Hz - 8.5KHz
Level Range	30 - 130 dB
Linearity Range	50dB / 100dB
Frequency Weighting	Analog
Time Weight	Slow
Microphone	1/2 inch polarization capacitance microphone
Power Supply	4pcs AA batteries
AC Output	4Vrms/ full bar graph, output impendence approx.600 ohm

Table 4.2: Specifications of decibel meter used

4.6 Questionnaires

There are multiple questionnaires used in this study including pre and post study questionnaire. The participants were required to fill out the pre study questionnaire after signed the consent form. Pre-study questionnaires include Pittsburgh Sleep Quality Index (PQSI) questionnaire, Adolescent/Adult Sensory Profile and Reduced Morningness-Eveningness Questionnaire[12][14]. Post study questionnaires also been used to check the subject's normal and intervention night's data. For this purpose, St. Mary's (or SMH) Sleep Questionnaire has been used.

4.6.1 Pittsburgh Sleep Quality Index (PQSI) questionnaire:

This questionnaire has been used in most of the sleep studies in order to check the effect of white noise on sleep quality. It is used to assess sleep quality over a previous 1-month time interval. the PSQI was designed to evaluate overall sleep quality in these clinical populations. Each of the questionnaire's 19 self-reported items belongs to one of seven subcategories: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. Five additional questions rated by the respondent's roommate or bed partner are included for clinical purposes and are not scored. Though there have been a variety of studies assessing the psychometric properties of the scale, the developers' initial evaluation found an internal reliability of a = .83, a test–retest reliability of .85 for the global scale, a sensitivity of 89.6%, and a specifi city of 86.5%. The main purpose of using this PSQI[42] questionnaire is to evaluate the how frequently the participants have experienced certain sleep difficulties over the past month and to rate their overall sleep quality. Scores for each question range from 0 to 3, with higher scores indicating more acute sleep disturbances.

4.6.2 reduced Morningness- Eveningness questionnaire (rMEQ)

The reduced Morningness-Eveningness questionnaire (rMEQ) has been used to measure whether a person's circadian rhythm (biological clock) produces peak alertness in the morning, in the evening, or in between[40]. The purpose of using this questionnaire was to assess individual differences in morningness and eveningness – the degree to which respondents are active and alert at certain times of day. Scale items query preferences in sleep and waking times, and subjective "peak" times at which participants feel their best[51].

Each section of the scale is assigned a value of 1 through 5. To obtain a global score, each item is totaled and the sum is converted to a 5-point scale: definitely morning type (70–86), moderately morning type (59–69), neither type (42–58), moderately evening type (31–41), and definitely evening type (16–30).

4.6.3 Adolescent/Adult Sensory Profile

The Adolescent/Adult Sensory Profile has been designed to promote self-evaluation of behavioral responses to everyday sensory experiences. Adolescent/Adult Sensory Profile helps measure sensory processing patterns and effects on functional performance. An individual answers questions regarding how the participant generally responds to sensations, as opposed to how the participant responds at any given time.

The main purpose of using Adolescent/Adult Sensory Profile was to examine the relationships between sensory-processing difficulties and sleep quality in adults. Also, how the participants responds to auditory sensations before providing the white noise during sleep.

4.6.4 St. Mary's (or SMH) Sleep Questionnaire:

Post study questionnaires also been used to check the subject's normal and intervention night's data. For this purpose, St. Mary's (or SMH) Sleep Questionnaire has been used. St. Mary's (or SMH) Sleep Questionnaire is an instrument that is a systematic inquiry into the subject's experience of sleep and that is composed of items of demonstrable reliability. In a psychometric evaluation conducted by Ellis and colleagues [2] , the scale possessed a test-retest reliability ranging from .70 to .96. Additional research on the part of developers supports the scale as a significant measure of change in sleep. As the scale solicits both Likert-type and fill-in-the-blank responses, the scale's scoring process has not been standardized and will depend on the specific purposes of the research or clinician. Some studies select only one or two of the scale's items to focus on (e.g., sleep latency), while others make use of results obtained on the entire instrument. As a measure designed to detect change, a respondent's results are primarily relevant when viewed in relation to results obtained at different times or by different individuals. St. Mary's (or SMH) Sleep Questionnaire is one of the most well-suited for repeated use across the span of a study or treatment period, the scale evaluates the duration and subjective quality of an individual's previous night's sleep. The scale's 14 items query a variety of sleep-related issues, including sleep latency, restlessness, nighttime waking, and morning alertness. Participants were required to fill out this questionnaire with or without white noise interventions.

4.7 Experimental Protocol

The experimental protocol has been divided into two types of protocol design i.e., Hardware based, and Questionnaire based. The data has been collected for a specific number of days for each protocol design. The participants were required to sleep with and without white noise for a specific number of days. And multiple questionnaires were provided to the participants before and after sleep. Also, Psychomotor Vigilance Task (PVT) has been provided to the participants that needed to be performed each time before filling out the questionnaire. The hardware-based data has been collected using a smart watch-based sleep monitor. For this purpose, the Fitbit Charge 4 and Charge 5 have been used.

4.7.1 Questionnaire Based Experiment

At the start of the study, participants were asked to fill out questionnaires. Some were pre-study questionnaires to check participants' previous sleep patterns, activity responses, and stress levels. The first one was the Pittsburgh Sleep Quality Index (PSQI) questionnaire which measures a person's previous month's sleep patterns. The second one was the Adolescent/Adult Sensory Profile which was a measure of a person's responses to sensory events in daily life. The third was the Reduced Morningness- Eveningness Questionnaire to check whether the person is a morning or an evening person. The last one was a three-minute Daily stress measurement task to check your daily stress level. This whole process took almost 35-40min before starting the study. And a post-study questionnaire was also involved i.e., St. Mary's Hospital Sleep Questionnaire to check participants' previous data collection night's experience.

After completing the questionnaire, on the assigned days, participants were asked to take part in sleep sessions with scheduled sleep patterns i.e., three consecutive nights each week and approximately eight hours of sleep each night. For week one, participants have been instructed to take eight hours of sleep with no noise. For week two, participants played white noise before and during sleep. And for week three, participants played placebo white noise during sleep. The data collection days have been randomized for each participant using the randomizer. At the end of three nights each week, participants filled out the post-study questionnaire. After the completion of data collection, participants have been asked to fill out a comfortability form regarding sleep changes participant felt with/without white noise. Figure 4.6 shows the flow of data collection which comprises of three weeks of sleep data and three consecutive days of each has been considered for providing sleep data and the other four days were the washout period.

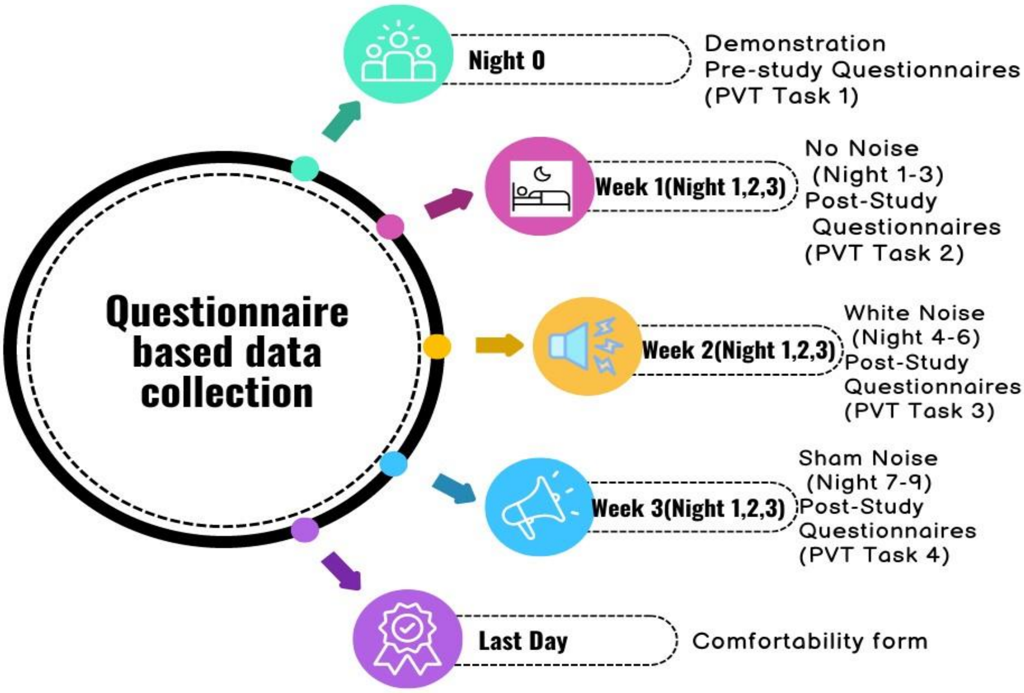


Figure 4.6: Flow diagram of questionnaire-based data collection

4.7.2 Hardware Based Experiment

In hardware-based data collection, participants were asked to fill out questionnaires, as well as using sleep monitoring device. All the questionnaire mentioned above i.e., PSQI questionnaire [42], Adolescent/Adult Sensory Profile [44] and Reduced Morningness-Eveningness Questionnaire as pre-study questionnaire. Also, St. Mary's Hospital Sleep Questionnaire[2] included as a post study questionnaire. Psychomotor vigilance task has been performed before filling out the questionnaire each time.

After completing the questionnaire, on the assigned days, participants were required to take part in sleep sessions with scheduled sleep patterns i.e., one week in total and approximately eight hours of sleep each night. The hardware set-up has been provided to participants which included the decibel meter and the wearable sleep monitoring device. The decibel meter was used to measure environmental noise. Whereas the sleep monitoring device was used to measure sleep data including sleep duration and sleep stages of each participant. The participants needed to wear the sleep monitoring device during sleep.

For this study, two white noise files were provided to participants. For night one, participants needed to take approximately eight hours of sleep with no noise. For the rest of the days, they have to hear white noise during sleep. At the end of each night, participants were required to fill out the post-study questionnaire. Once the data has been collected, each participant has been asked for their comfort ability level on sleep changes they feel with/without white noise. Figure 4.7 shows the flow of data collection which comprises of one week of sleep data in which participant have to sleep with no noise for one night and with white noise for two consecutive nights. And participants must sleep with sham noise for two consecutive nights as well to check the effect of noise on sleep latency duration and to check whether the effect of sham noise persists for whole night or not.

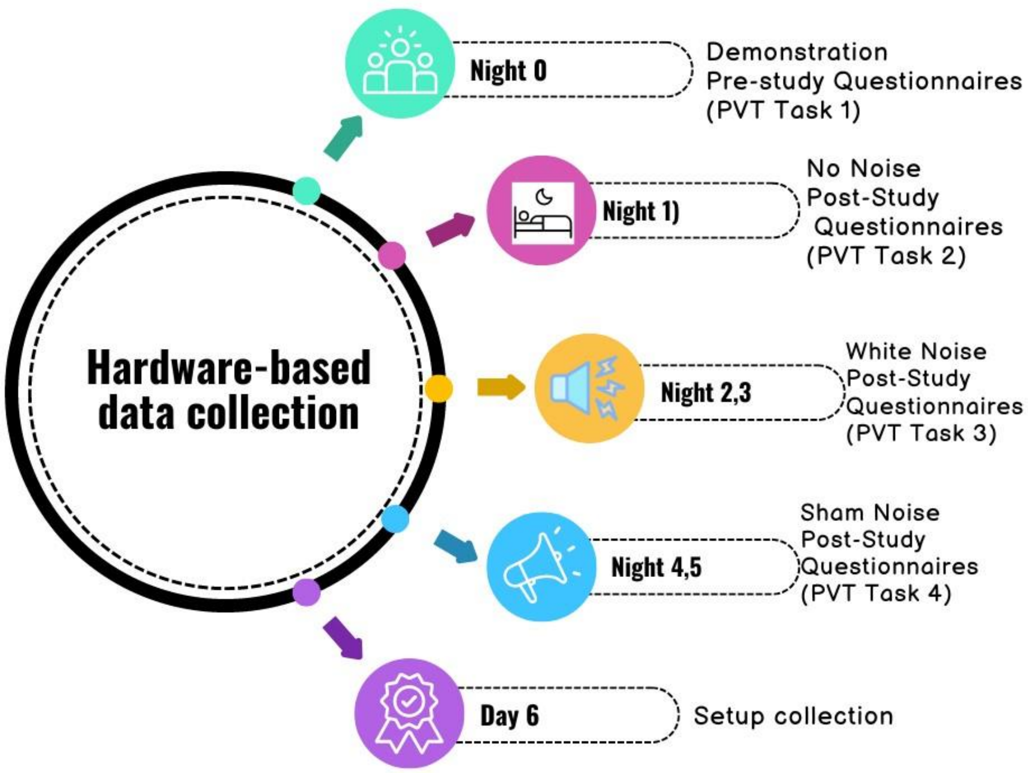


Figure 4.7: Flow diagram of hardware-based data collection

The illustration in Figure 4.8 displays the configuration presented to participants for the purpose of hardware oriented experimental protocol design. The hardware ensemble encompassed a decibel meter, white noise generator, Fitbit watch synchronized with its corresponding mobile application, questionnaires, and a psychomotor vigilance task. Participants were instructed to log into the Fitbit application using their personal mobile phones, and configurations were adjusted in accordance with their Body Mass Index (BMI). The provision of white noise was also arranged; it was activated on participants' mobile phones or laptops based on the availability of respective devices and their charging status, ensuring continuous playback throughout the entire night.

The placement of the white noise emitting device, whether it be a mobile phone or a laptop, occurred at a distance of approximately 3 to 6 feet from the bed. Furthermore, a deliberate arrangement was made to ensure that the white noise emitting device and the decibel meter were situated in a manner such that the speaker of the white noise device maintained a parallel orientation with the microphone sponge of the decibel meter.

4.8 Statistical Analysis

Multiple types of data collection tools have been used to collect data for this study and depending upon the type of data various statistical analysis tools have been employed. This study encompasses two types of protocol designs: questionnaire-based and hardware-based.

4.8.1 Hardware Based statistical analysis.

In the hardware-based protocol, the Fitbit charge 4 and5 have been used to measure the sleep factors of the subject for the whole night. The Fitbit sleep monitoring feature provides data, which must be interpreted to score the various sleep aspects. This covers variables including overall sleep duration, light, deep, and REM sleep stages, as well as sleep efficiency and sleep onset latency. While sleep phases show the distribution of various sleep cycles throughout the night, total sleep time is the amount of time a subject can spend sleeping from the moment to fall asleep until one can wake up. An overall indicator of the quality of one's sleep, sleep efficiency is the ratio of time in bed to time asleep. Furthermore, sleep onset latency gauges how long it takes someone to fall asleep after turning in for the night. Through the analysis of these sleep characteristics, users can acquire valuable information on the excellence and length of their sleep, enabling them to make necessary modifications to enhance their overall sleep well-being.

As the data collection involves parameters such as total sleep time, total sleep score, deep sleep duration, light sleep duration, and REM sleep duration, all gathered through Fitbit smartwatches. Statistical analysis of this quantitative data includes ANOVA tests to compare means across different conditions, followed by post hoc tests to identify specific differences. ANOVA tests have been performed on each type of data. Which compares the mean +/-std values of each subject sleeping with no noise white noise and sham noise.

4.8.2 Questionnaire Based statistical analysis

On the other hand, the questionnaire-based protocol includes scoring from multiple questionnaires, namely the Pittsburgh Sleep Quality Index (PSQI), reduced Morningness-Eveningness Questionnaire (rMEQ), Adult/Adolescent Sensory Profile (AASP), and St. Mary Questionnaire.

In the reduced morningness-eveningness questionnaire, each section of the scale is as signed a value of 1 through 5. To obtain a global score, each item is totaled, and the sum is converted to a 5-point scale: definitely morning type (70–86), moderately morning type (59–69), neither type (42–58), moderately evening type (31–41), and definitely

evening type (16–30). The scoring has been done manually for this questionnaire. The collected data was insufficient for comparison as most of the subjects were standing in the category of neither morning nor evening type, that's why no statistical tests applied on this data.

Statistical techniques have been applied on the remaining three questionnaires. The Sensory Profile for Adolescents and Adults (AASP; Brown) Dunn (2002). Respondents provide answers to questions regarding their reactions to everyday sensory events in this self-reporting tool. There are sixty things in total, with questions covering every sensory modality. The sixty items are scored by equally dividing them into four sub- scales, or quadrants, which represent the four distinct types of sensory processing—low regulation, sensation seeking, sensory sensitivity and sensation avoiding—based on factor analysis. Using a 5-point Likert scale, participants indicate how frequently they react to the sensory encounter in the way that is described in the items (1 being nearly never, and 5 being very constantly). Each quadrant's final score falls between 5 and 75. Using national samples of 950 adolescents and adults (ages 11 through 90 years), cutoff scores have been calculated to indicate when scores are significantly different from their peers' responses. Each age group (11–17; 18–64; 65 and older) has its norms. The AASP manual defines five categories of responses for the sensory processing patterns: much less than most people (2% of the population); less than most people (14% of the population); like most people (68% of the population); more than most people (14% of the population) and much more than most people (2% of the population). Using national samples of 950 adolescents and adults (ages 11 through 90 years), cutoff scores have been calculated that indicate when scores are significantly different from their peers' responses. Each age group (11–17; 18–64; 65 and older) has its norms. The AASP manual defines five categories of responses for the sensory-processing patterns: much less than most people (2% of the population); less than most people (14% of the population); like most people (68% of the population); more than most people (14% of the population) and much more than most people (2% of the population).

The PSQI, or Pittsburgh Sleep Quality Index, was developed by Buysse, Reynolds, Monk, Berman, and Kupfer in 1989. This standardized subjective sleep quality measure is applied in research and therapeutic contexts. The tool is a questionnaire with 19 questions, separated into seven subscales that each represent a distinct element of inadequate sleep. The subscales comprise total sleep duration, which represents the average number of hours of sleep per night; sleep latency, which measures the average time taken to fall asleep while lying in bed (in minutes); the rate of daytime dysfunctions associated with inadequate sleep at night (e.g., fatigue, inability to stay awake during the day); sleep efficiency, which represents the percentage of total time in bed that is spent sleeping; the type and frequency of nighttime sleep disturbances (e.g., nightmares, nocturia, pain); and subjective assessment of sleep quality. In order to analyze, the questionnaire has taken as pre study questionnaire i.e., filled before subject taking part in sleep study. Subjects are asked to consider how much they have slept during the past month. Subscales are converted and coded to a Likert scale with four points (0–3) and totaled to create a global score that measures the overall quality of sleep over the previous month on a worldwide scale. The continuous global sleep quality scores range from 0 to 21, with higher scores denoting lower sleep quality. When the cutoff score is greater than 5, it indicates poor quality sleep. Sleep durations of less than seven hours, sleep latency of more than fifteen minutes, and sleep efficiency of less than 85% are examples of higher scores that indicate poor quality of sleep. When it comes to therapeutic objectives, scores above the cutoff point for poor sleep quality could mean that insomnia is present.

The St. Mary questionnaire scoring process entails evaluating the replies given by individuals regarding the quality of their sleep on the previous night. Usually, every item in the questionnaire is given a numerical value or rating that corresponds to the participant's response. These ratings may indicate factors such as the time it takes to fall asleep, the length of sleep, the number of times waking up, and the general perception of sleep quality. After collecting all the responses, the scores can be computed or evaluated based on preset criteria to produce the overall rating of sleep quality. Typically, higher scores on the St. Mary questionnaire are associated with lower sleep quality, whereas lower values imply better sleep results. In this study, the ninth question i.e., how well did you sleep last night? of St. Mary questionnaire has been considered for analysis purposes.

As the collected data from questionnaires is qualitative, chi-square tests are applied to analyze the relationships between variables. Notably, due to insufficient data in the rMEQ category, statistical analysis could not be performed. However, for the other questionnaires, chi-square tests were conducted to compare scores and assess the impact of white noise on sleep quality. Specifically, chi-square tests were used to analyze the relationship between PSQI data and Adult Sensory Profile data, as well as between PSQI data (pre-study) and St. Mary Questionnaire data (post-study), providing insights into the effectiveness of white noise intervention on sleep quality.

Chapter 5 : IMPLEMENTATION AND RESULTS

5.1 Hardware Based

The sleep quality was accessed by multiple parameters measured by using sleep monitoring device. The parameter includes total sleep score, total sleep time and sleep stages i.e., light sleep, deep sleep and REM sleep.

5.1.1 Decibel meter

The decibel meter has also been used to measure the environmental noise. The instrument used in this study has a measurement range of 30 - 130 dB. The AC output has been collected to visualize the noise output. The decibel meter was exposed to the data collection environment i.e., university hostel rooms and home environment. A decibel meter measured the environmental noise on no-noise days as well as on intervention days to check the difference in environmental noise. For intervention, white noise of 0 dbW was generated. The signal power was kept constant for 8 hours. The white noise signal for active control condition was generated with 0 dBW for 30 min, which was reduced in intervals of 5 dBW every 3 minutes to reach -50 dBW for smooth reduction in the amplitude/volume. The following 7 hours of active control signal had a power of -60 dbW. The decibel meter collected the environmental noise in decibels whose mean+/-std values are presented in the table 5.1. The graph 5.1 shows the difference in environmental noise on 5 days of data collection i.e., no noise, white noise day 1, white noise day 2, sham noise day 1, and sham noise day 2. This has been interpreted from the graph that the noise level on no noise day was about 54dB. Whereas, the noise level on noise intervention days was about 60 dB.

Noise Type	Mean value	Std value
No noise	53.06	10.24341
White noise day 1	61.3108	9.365283
White noise day 2	61.8924	9.687672
Sham noise day 1	60.2112	14.14037
Sham noise day 2	55.59	11.57989

Table 5. 1**:** Mean +/-std values of environmental noise on no noise and noise intervention

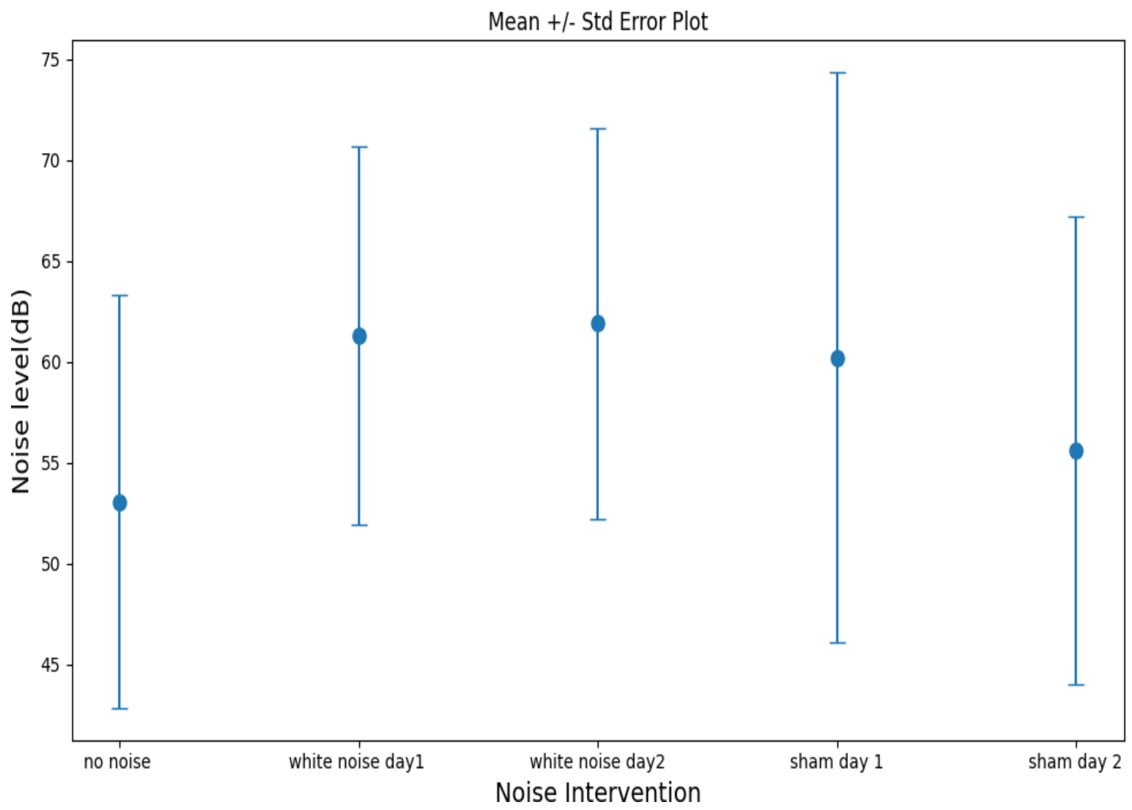


Figure 5.1: Graph of mean +/-std values of environmental noise on no noise, sham noise and white noise intervention days

5.1.2 Sleep Monitoring Device

The data has been collected for 27 subjects. The overall sleep score shows that there is no significant effect of white noise on sleep quality.

The graph in fig 5.2 shows that the current effect of the white noise on total sleep score is $F(2,52)=0.26702$ and having the p-value of 0.76670. This shows no significant effect of noise on sleep quality. The white noise also has no significant effect on total sleep time with or without noise.

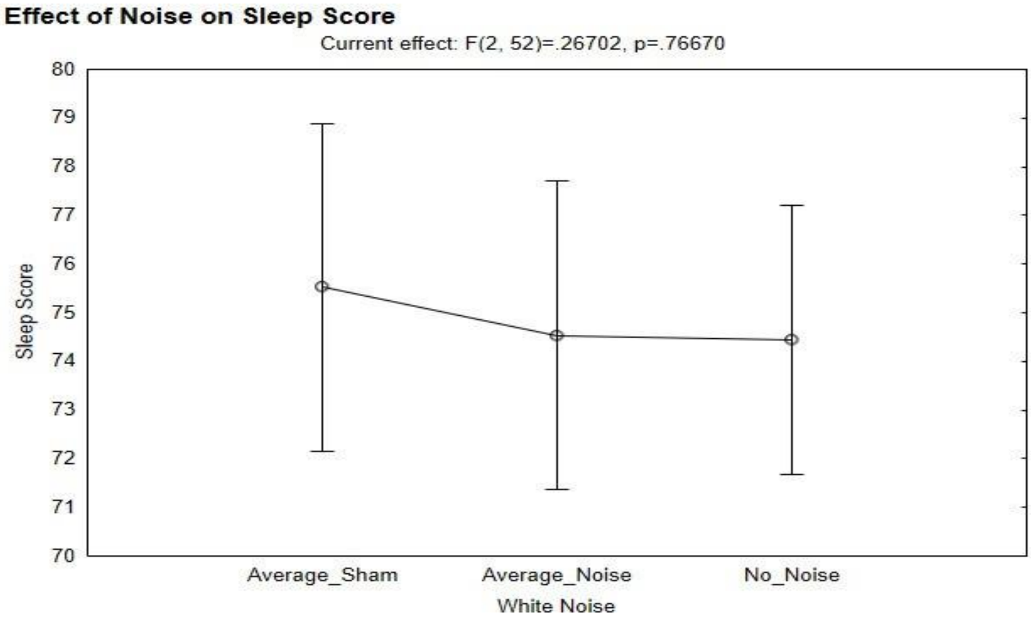


Figure 5. 2: Mean +/- std plot of total sleep score to check the effects of white noise on overall subject's sleep

The graph in fig. 5.3 shows that the current effect of the white noise on total sleep duration in F(2,52)=1.0341 and having the p-value of 0.36274. This shows no significant effect of noise on sleep quality. We have also performed post hoc tests however the results are not significant.

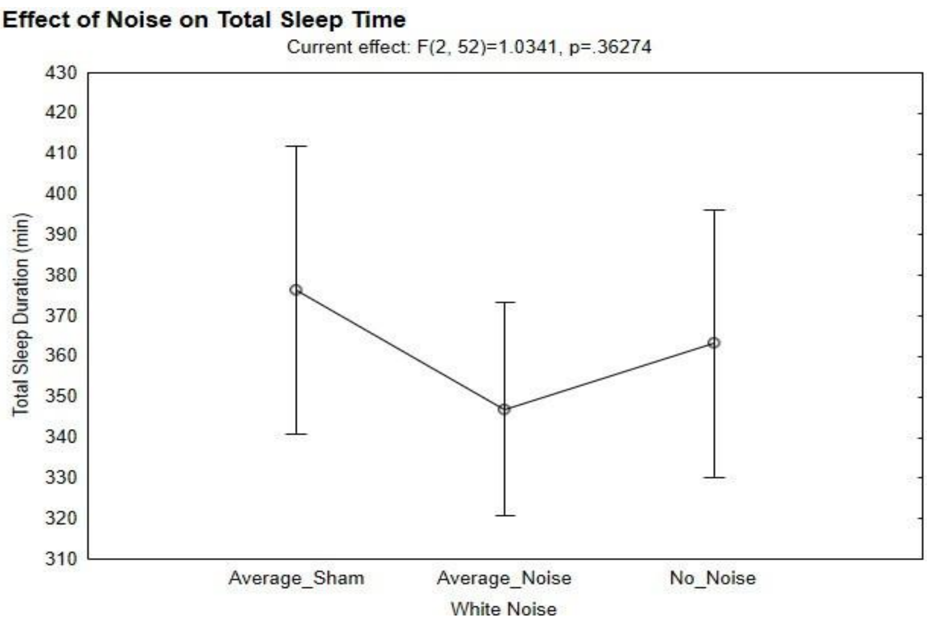


Figure 5. 3: Mean +/- std plot of total sleep duration to check the effects of white noise on overall subject's minutes of sleep

Further, the statistical analysis also applied on all the sleep stages i.e., Light sleep, REM sleep and Deep sleep to test effect of white noise on the sleep quality. The data of light sleep in figure 5.4 shows that the persons sleeping with or without white noise have the same duration of light sleep. The statistical results show the current effect of white noise on light sleep are $F(2,52)= 1.0865$ having the p-value of 0.34493. This results also leads us to non-significant output.

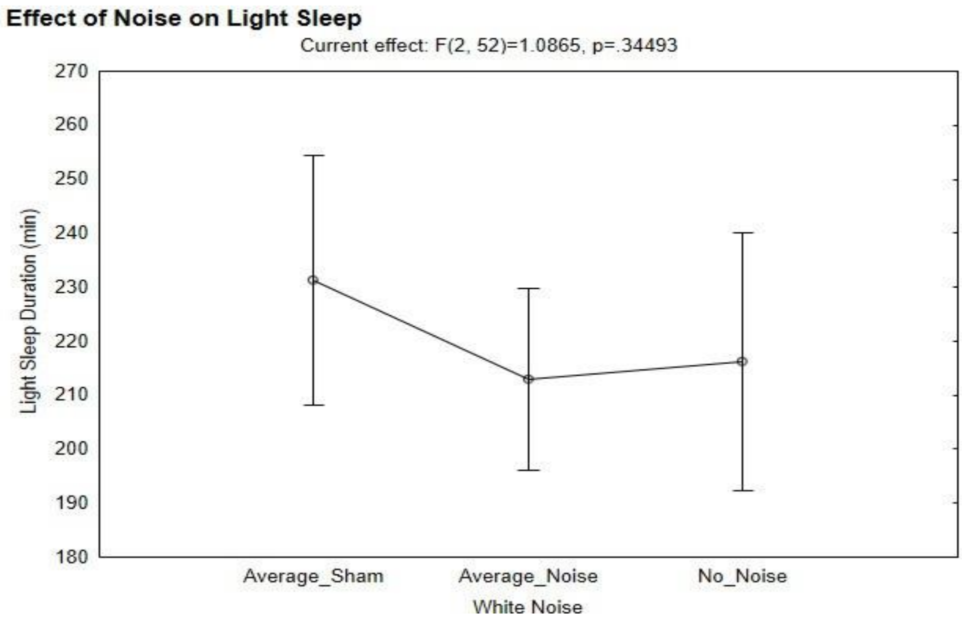


Figure 5. 4: Effects of white noise on light sleep based on Mean+/- std values of light sleep duration having $F(2,52)=1.08$ and ($p=0.345$)

Deep sleep statistical graph shown in figure 5.5 shows current effect of $F(2,52)=1.0708$ with the p-value of 0.3506. This leads to the non-significant effect of white noise on sleep quality. We have also used the post hoc tests but the results are non-significant.

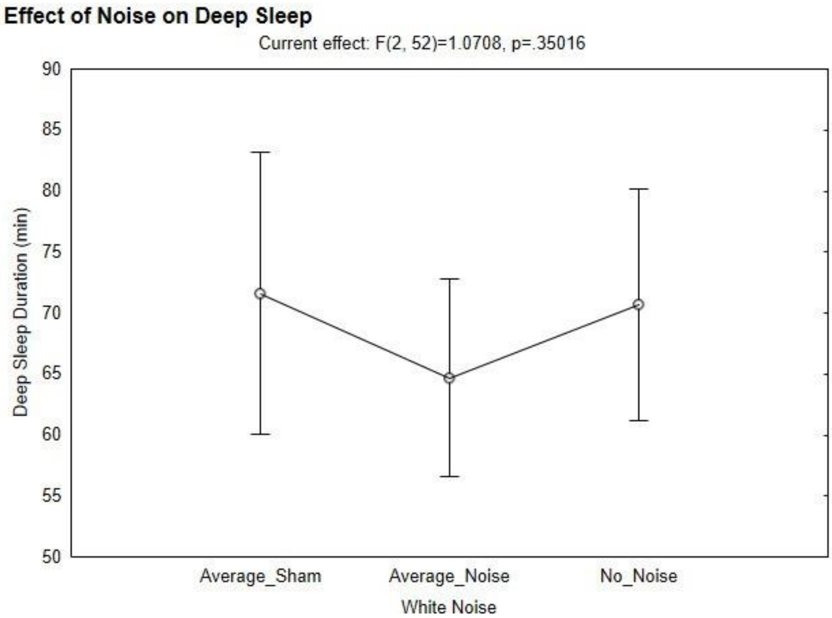


Figure 5. 5: Mean+/- std plot of deep sleep duration having F(2,52)=1.0708 and (p=0.35)

Another test performed was effect of white noise on REM sleep duration. The graph in fig 5.6 shows the current effect F(2,52)= 0.25033 with the p-value of 0.7794. These statistics shows that the results are non-significant and there is no effect of white noise on any of the sleep stages as well.

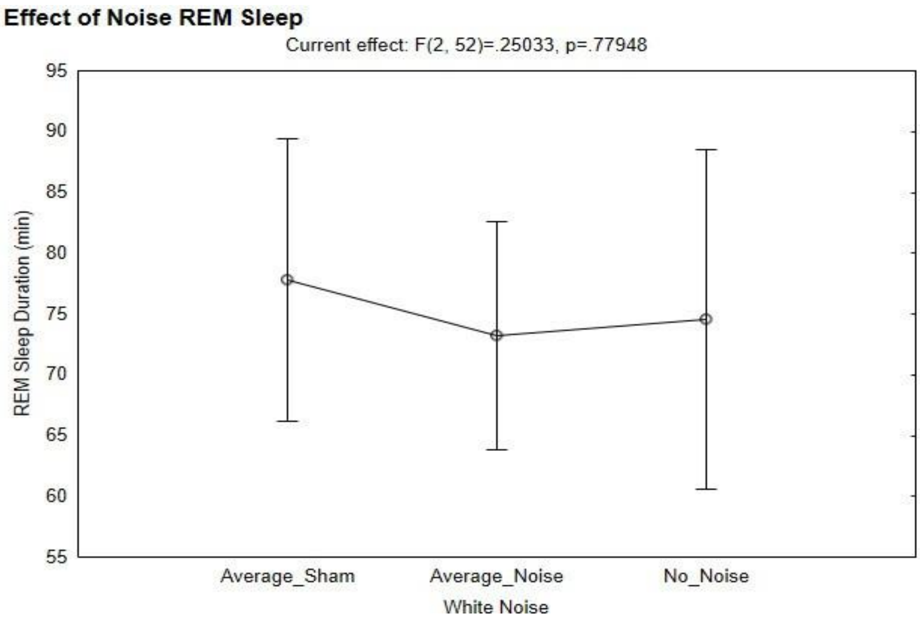


Figure 5.6: Effects of white noise on REM sleep duration based on Mean+/- std values of REM sleep duration having F(2,52)=0.25033 and (p=0.78)

5.2 Questionnaire Based

Multiple questionnaires have been filled by the subjects. The subject shows variants of responses regarding those questionnaires. Statistical analysis techniques have been applied to that data to check the variations between subjects sleeping without any noise or sleeping with white noise.

5.2.1 reduced Morningness Eveningness Questionnaire(rMEQ)

In the reduced morningness-eveningness questionnaire, each section of the scale is as- signed a value of 1 through 5. To obtain a global score, each item is totaled and the sum is converted to a 5-point scale: definitely morning type to definitely evening type. The scoring has been done manually for this particular questionnaire. The rMEQ questionnaire has been collected from 94 subjects out of which 75 subjects were neither morning type nor evening type which makes 80 percent of the total population. This means data is insufficient to apply any statistical implications.

5.2.2 PSQI vs AASP

In this study, PSQI has been compared with the AASP to check the correlations be- tween sensory processing patterns and sleep quality measures. The sensory patterns measures were collected using the Adult sensory profile, whereas, the sleep quality measures were taken as good or poor sleepers from the PSQI questionnaire. This data makes us check the differences in sensory-processing patterns between good versus poor sleepers. The data has been collected from two types of subjects the subjects who had used hardware for sleep quality monitoring lately i.e., 24 no subjects from which good sleepers= 7 and poor sleepers=17 subjects. Chi-square tests have been performed to check the comparison between sensory measures and sleep quality. The results show non-significant differences among all the quadrants indicated as low registration ($p = 0.074$), sensation seeking ($p = 0.265$), sensory sensitivity ($p = 0.257$), and sensation avoiding ($p = 0.490$). Figure 5.9 and 5.10 shows the relationship between both AASP and PSQI questionnaires.

Hardware Based												
	GOOD SLEEPERS(n=7)					POOR SLEEPERS(n=17)						
	Less than Most People	More than Most People	Much Less than Most People	Much More than Most People	Similar to Most People	Less than Most People	More than Most People	Much Less than Most People	Much More than Most People	Similar to Most People	CHI SQUARE	P-VALUE
LOW REGISTRATION	0	14.3	0	28.6	57.1	0	31.3	0	0	68.8	5.209	0.074
SENSATION SEEKING	57.1	0	0	0	42.9	25.0	0	12.5	0	62.5	2.654	0.265
SENSORY SENSITIVITY	14.3	0	0	14.3	71.4	0	18.8	0	25.0	56.3	4.040	0.257
SENSATION AVOIDING	14.3	28.6	0	28.6	28.6	0	31.3	0	31.3	37.5	2.420	0.490

Figure 5. 7: Hardware based subjects percentages of Good Versus Poor Sleepers Be- low (<), At (=) or Above (>) the Typical Performance Category in Each Sensory processing Quadrant

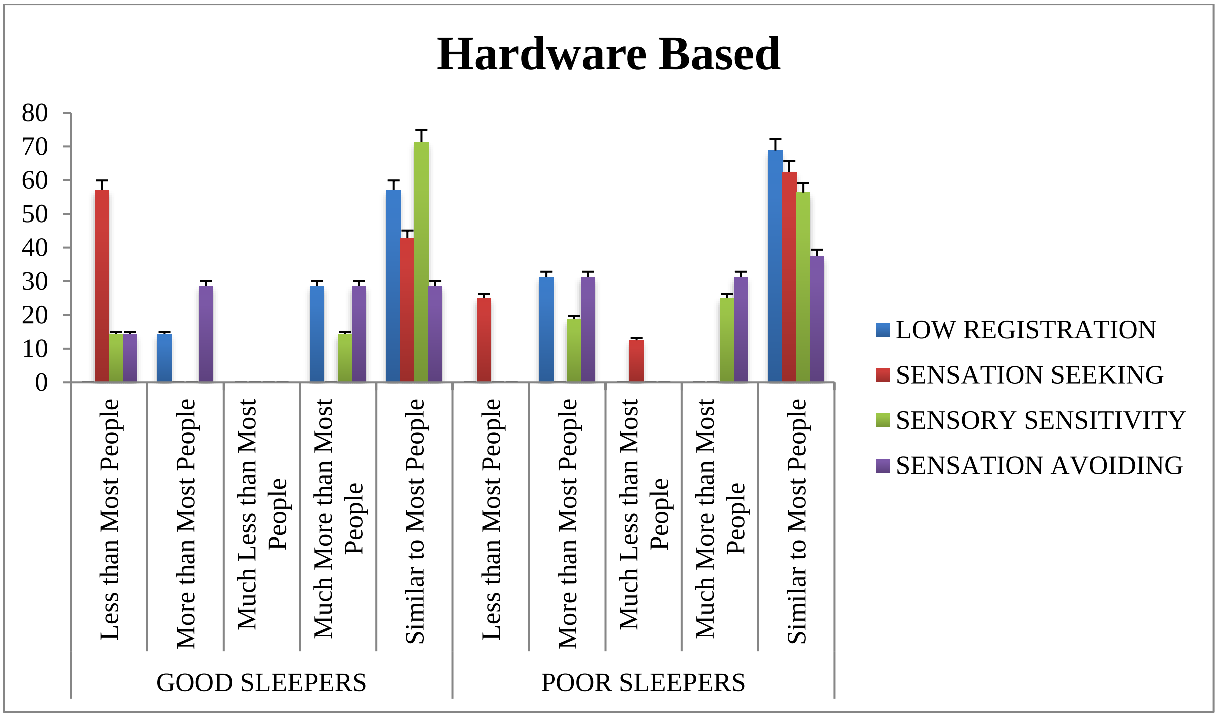


Figure 5.8: Graph of hardware based Good Versus Poor Sleepers Below (<), At (=) or Above (>) the Typical Performance Category in Each Sensory processing Quadrant

Similarly, the same chi-square tests were performed on all the questionnaire-based subjects before taking part in the study to check the relation between sensory measures and sleep quality. About 94 subjects have filled out both the questionnaire from which (n =23) were claimed as good sleepers and (n=71) were categorized as poor sleepers based on the PSQI scoring index. The chi-square result shows an insignificant relation between sensory data and sleep quality measures. The chi-square test shows (p=0.466) for low registration data, (p=0.273) for sensation seeking, (p = 0.458) for sensory sensitivity, and (p =0.145) for sensation avoiding. When examining the various modalities, poor sleepers as well as good sleepers showed no significant difference in sensory response.

	GOOD SLEEPERS(n=23)					POOR SLEEPERS(n=71)						
	Less than Most People	More than Most People	Much Less than Most People	Much More than Most People	Similar to Most People	Less than Most People	More than Most People	Much Less than Most People	Much More than Most People	Similar to Most People	CHI SQUARE	P-VALUE
LOW REGISTRATION	26.1	13.0	13.0	4.3	43.5	21.1	16.9	4.2	1.4	56.3	3.715	0.446
SENSATION SEEKING	21.7	21.7	13.0	0	43.5	40.8	11.3	7.0	0	40.8	3.895	0.273
SENSORY SENSITIVITY	4.3	30.4	8.7	13.0	43.5	5.6	26.8	1.4	21.1	45.1	3.632	0.458
SENSATION AVOIDING	8.7	26.1	4.3	8.7	52.2	2.8	22.5	1.4	33.8	39.4	6.832	0.145

Figure 5.9: Questionnaire based subjects percentages of Good Versus Poor Sleepers Below (<), At (=) or Above (>) the Typical Performance Category in Each Sensory processing Quadrant

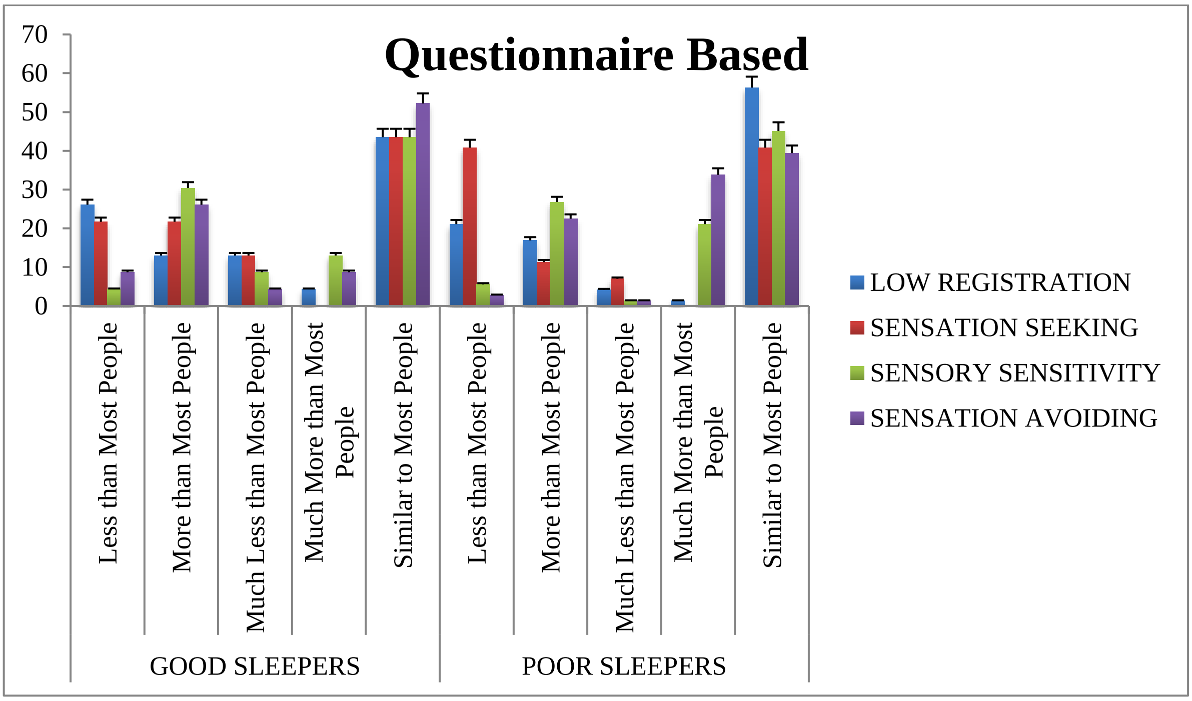


Figure 5.10: Graph of questionnaire based Good Versus Poor Sleepers Below (<), At (=) or Above (>) the Typical Performance Category in Each Sensory processing Quadrant

5.2.3 PSQI vs St. Mary questionnaire

At the beginning of data collection procedure, subjects were recruited to fill the PSQI questionnaire i.e., provides the sleep quality index based on previous month sleep cycle. After the noise intervention, the St Mary questionnaire was collected from both hardware-based and questionnaire-based subjects to check the difference between the sleep quality index of good and bad sleepers before and after the noise intervention to check the improvement level.

For hardware-based subjects, the collected data has no of good sleepers were n=9 and no of poor sleepers n=18, results show no significant difference between the sleep quality of good and poor sleepers for all three interventions i.e., no noise, white noise, and sham noise. For no noise, the chi-square value is 1.879 which gives the (p-value = 0.785), for white noise intervention the chi-square value is 1.850 with the (p =0.763), and for the sham intervention of white noise chi-square =1.25 and (p = 0.741). All these p-values are greater than p >0.05 which indicates that there is no significant effect of white noise on good and poor sleepers. Their quality of sleep almost remains the same in sleeping without noise intervention and sleeping with white noise intervention. The table 5.11 and graph 5.12 show the results of sleep quality.

Hardware Based												
	GOOD SLEEPERS(n=9)					POOR SLEEPERS(n=18)						
	Well	Fairly Well	Very Well	Badly	Fairly Badly	Well	Fairly Well	Very Well	Badly	Fairly Badly	CHI SQUARE	P-VALUE
No Noise	22.2	66.7	11.1	0.0	0.0	16.7	61.1	5.6	11.1	5.6	1.879	0.758
White Noise	22.2	44.4	33.3	16.7	0.0	16.7	27.8	22.2	27.8	5.6	1.850	0.763
Sham Noise	44.4	33.3	11.1	0	11.1	27.8	50.0	16.7	0	5.6	1.250	0.741

Figure 5.11: Hardware based subjects percentages of Good Versus Poor Sleepers with the percentage of improvement in sleep quality between no noise, white noise and sham noise

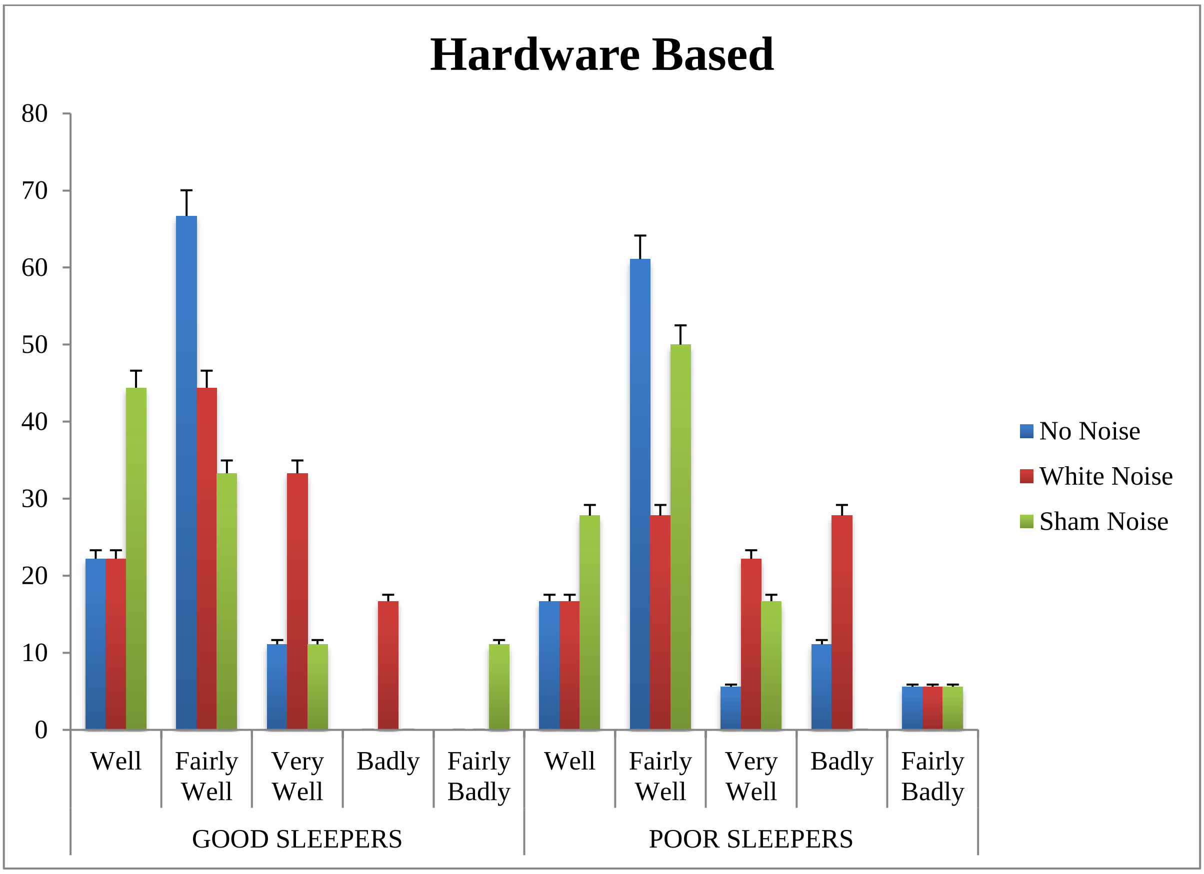


Figure 5.12: Graph of subjects percentages of Good Versus Poor Sleepers with the percentage of improvement in sleep quality between no noise, white noise and sham noise

For questionnaire-based subjects, the total no of poor sleepers was n=59, and no of good sleepers was n=13. However, the results show no significant difference between the sleep quality of good and poor sleepers for all three interventions i.e., no noise, white noise, and sham noise. For no noise, the chi-square value is 3.635 which gives the (p-value = 0.603), for white noise intervention the chi-square value is 4.990 with the ($p = 0.288$), and for the sham intervention of white noise chi-square =8.605 and ($p = 0.126$). All these p-values are greater than $p > 0.05$ which indicates that there is no significant effect of white noise on good and poor sleepers. Their quality of sleep almost remains the same in sleeping without noise intervention and sleeping with white noise intervention. The table 5.13 and graph 5.14 shows the effect of no noise, sham noise and white noise on good and bad sleepers.

Questionnaire Based												
	GOOD SLEEPERS(n=13)					POOR SLEEPERS(n=59)						
	Well	Fairly Well	Very Well	Badly	Fairly Badly	Well	Fairly Well	Very Well	Badly	Fairly Badly	CHI SQUARE	P-VALUE
No Noise	30.8	38.5	15.4	0.0	15.4	33.3	41.0	5.1	7.7	7.7	3.635	0.603
White Noise	23.1	53.8	23.1	0.0	0.0	43.6	33.3	10.3	5.1	7.7	4.990	0.288
Sham Noise	15.4	46.2	38.5	0.0	0.0	48.7	23.1	15.4	5.1	5.1	8.604	0.126

Figure 5.13: Questionnaire-based subjects percentages of Good Versus Poor Sleepers with the percentage of improvement in sleep quality between no noise, white noise and sham noise

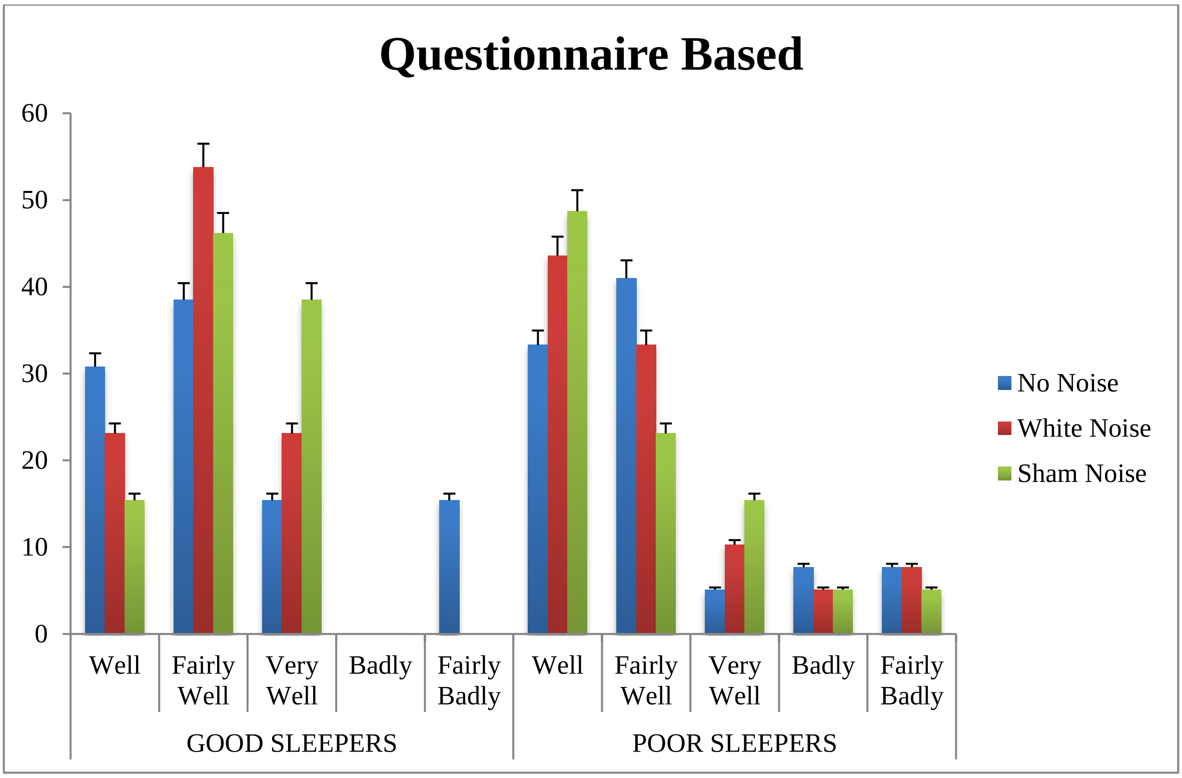


Figure 5.14: Graph of subjects percentages of Good Versus Poor Sleepers with the percentage of improvement in sleep quality between no noise, white noise and sham noise

Chapter 6: DISCUSSION

White noise is purported to mask disruptive noises in the bedroom environment and be a non-pharmacological approach for promoting sleep and improving sleep quality. Some previous studies suggested that various broadband noises are used as a non-pharmacological treatment for better sleep. However, the efficacy of noise to improve sleep measures remained unclear. Multiple studies have been performed to evaluate the effects of broadband noise on sleep, but due to the small sample size, no statis- tical analysis, use of imprecise noise measurement tools, and uncontrolled disruptive factors, the research was inconclusive. Therefore, there was a need to test the ratio of improvement using reliable and large-scale data collection and analysis tools under controlled conditions.

The study aims to quantify sleep quality, sleep fragmentation, sleep latency, and relevant sleep factors by providing white noise to the students and to assess whether broadband noise can be a non-pharmacological treatment for better sleep quality. For this purpose, multiple sleep questionnaires as well as sleep monitoring devices have been used. Questionnaire-based data involves multiple pre-and post-study questionnaires (including the Pittsburg Sleep Quality Index (PSQI), Adult/Adolescent Sensory Profile (AASP), reduced Morningness-Eveningness Questionnaire (rMEQ), and St.Mary Questionnaire along with psychomotor vigilance task(PVT). Whereas, Hardware-Based studies involve pre-and post-study questionnaires, decibel meter data to measure environmental noise, psychomotor vigilance task (PVT), and mainly sleep monitoring devices to provide information about sleep stages and other sleep factors including sleep score, deep sleep duration, light sleep duration, REM sleep duration and total sleep time.

In this study both hardware and questionnaire were involved as mentioned above. The sleep monitoring device i.e., Fitbit charge 4 and 5 were used to check the sleep stages and other sleep factors on 27 number of healthy and subject with minor sleep issues. The reason behind using Fitbit is the accuracy level of the device. The sensitivity and specificity of total sleep, light sleep, deep sleep, and REM sleep were investigated for each sleep stage in the Fitbit Inspire FBI2 and PSG by EBE analysis. For total sleep, FBI2 had low specificity (13.1%), high sensitivity (93.9%), and moderate-to-low accuracy (76.0%). For light sleep, FBI2 showed a relatively low sensitivity (54.3%), specificity (62.3%), and accuracy (59.1%), while sensitivity to deep sleep (84.8%) and REM sleep (86.4%) was moderate. However, the accuracy was high for deep (98.2%) and REM sleep (92.3%). Deep sleep (50.1%) and REM sleep (59.1%) showed a moderate-to-low specificity [40]. Similarly, another study suggests that Fitbit Charge 4 has great accuracy than other devices. Compared with polysomnography (PSG), Actiwatch Spectrum Pro (AWS) and Fitbit Charge 4 (FBC) showed great accuracy (86.9% vs. 86.5%) and sensitivity (detecting sleep; 92.6% vs. 89.9%), but comparatively poor specificity (detecting wake; 35.7% vs. 62.2%). Both devices showed better accuracy in assessing sleep than wakefulness, with the same sensitivity but statistically different specificity[2].

In this study, the results showed that there is no significant effect of white noise on the sleep quality of the subject' overall sleep score along with the total sleep time. Fitbit also provided us data on all the sleep stages i.e., light sleep duration, deep sleep duration, and REM sleep duration individually but the results remain insignificant which implies that there is no effect of white noise or sham noise intervention on a person's sleep quality or quantity. Previously, another researcher used AC sound to check the effect of noise on sleep quality and recorded the data using an actigraph unit wristwatch set. The results also suggested that AC sound had no significant positive effect on sleep duration, latency, and efficiency[4]. Another researcher used Motionlogger Actigraph showed improved sleep quality. The setting of this particular study was High environmental noise in New York City with a lesser no of subjects i.e., n=10 and no control on external noise which makes the results of the study less reliable [45]. In this study, the decibel meter has been used to measure environmental noise in no noise and on white noise intervention days which make the external noise more controllable. Also, a greater sample size of n=27 has been included. The data has been collected using sleep monitoring devices as well as using questionnaires so that there is less efficacy of error.

6.1 PSQI vs St Mary and AASP

In this study the aim of the study is to check whether white noise does affect good or bad sleepers using multiple questionnaires. For this check the PSQI questionnaires were taken from the subjects. The data of PSQI vs AASP shows that Sleep quality does not significantly correlate with sensory-processing patterns characterized by hypersensitivity. These patterns were manifested in specific modalities (tactile, visual, and auditory), which least significantly predicted sleep quality. Predisposing, sensory- processing patterns specifically, hypersensitivity may be linked to the quality of sleep.

When treating patients with SPD or those who have trouble sleeping, occupational therapists discussed the potential connection between Sensory Processing Disorder (SPD) and sleep quality. This could improve performance and quality of life and help implement the best intervention based on the individual's needs.[52] Previously, most of the studies were done by using EEG, PSG, and questionnaires i.e., sleep diaries and PSQI questionnaire. A dose-response association was seen by Terzano and colleagues [53] between sound pressure levels and sleep outcome. The properties of noise and its effects on sleep onset latency, sleep fragmentation, sleep quality, and length of sleep and wake- fulness did not appear to be significantly correlated. The results for sleep duration and quality were frequently in line with each other. In other words, the quality of sleep was either positively correlated with overall sleep duration or negatively correlated with waking up after sleep onset. If the quality of sleep was unaffected by constant noise then it frequently did not affect how long they slept for or woke up after falling asleep. For instance, Terzano and colleagues [54], [55] discovered that noise pollution increased wakefulness following the onset of sleep and decreased both the quality and duration of sleep.

Continuous noise was found to decrease sleep onset latency in observation studies when parents or study investigators reported on their child's or patient's sleep, respectively. Significant improvements in self-reported sleep onset latency in the Gragert[46] study corroborated the study investigators' observation that patients fell asleep over an hour faster when exposed to continuous noise. Patients with severe tinnitus also reported less difficulty falling asleep when there was constant noise[56]

Additionally, there was evidence that the constant noise from the hospital lessened the fragmentation of sleep caused by the noise. For instance, Stanchina and associates [57] discovered that persistent noise decreased sleep fragmentation in healthy adults subjected to recorded noise from intensive care units, and came to the conclusion that noise that was continuous raised arousal thresholds by decreasing the gap between background and peak noise levels. The idea that continuous noise raises the threshold for detecting sounds and masks other sounds to promote better sleep is supported by this result; nevertheless, there is insufficient evidence in the examined literature to support or deny any of the theories. In contrast to the notions regarding the benefits of continuous noise on sleep, adding continuous noise to the bedroom may cause health issues in addition to disrupting sleep. There is some evidence from the study that loud noises keep you from falling asleep. However, the effects of white noise disruption on sleep duration, quality, and fragmentation increased as sound pressure intensity rose [38].

For the comparison of the difference in sleep quality of good and poor sleepers before and after white noise the PSQI and St. Mary questionnaires have been collected. The data also reveals that there is no improvement in sleep quality after exposure to white noise. According to previous studies, some suggest that there is no significant effect of white noise on sleep quality, however remaining reports are otherwise. However, the lag in those studies was less sample size, uncontrolled environmental noise, fewer data collection days, and no proper statistical analysis, also most of the studies were done on patients and infants. The frequency weighting of the noise levels was not disclosed in much earlier research, which made it impossible to compare differentially weighted levels because the overall level is strongly reliant on the frequency spectrum of the noise.

This study also suggested that white noise has no significant effect on sleep quality. However, the results are based on the facts having a large sample size, controlled environmental noise, monitored white noise level, and data collected for both noise and white noise. A sham noise group has also been involved to check the effect on sleep latency duration. The data collection has been done for 1 week for hardware-based subjects and 3 weeks (3 days each week) for questionnaire-based subjects, which means the data collection duration is enough to claim the results. Also, both a sleep monitoring device and multiple questionnaires were involved to lessen the degree of inaccuracy in the data. The claimed results are based on proper statistical analysis tools i.e., chi-square and ANOVA applied to questionnaire and hardware-based data respectively.

6.2 Limitations

The study was performed on 54 questionnaire-based subjects and 27 hardware-based subjects. However, the gender ratio was not the same. Gender balance may provide better results. Also, the study was not able to distinguish between the morning and evening subjects due to the lesser sample size of rMEQ data. The study was not bound to the sleeping time of the subject. Some subjects take less than 8 hours of sleep whereas some exceed the duration of 10-12 hours.

Chapter 7: CONCLUSIONS AND FUTURE RECOMMENDATIONS

Sleep is a fundamental physiological process essential for maintaining physical and psychological well-being. Quality sleep is related to multiple valued performances in human life, including maintaining health and improving outcomes at work. Disturbance of sleep can increase the morbidity rate and can create multiple physical and mental disorders. Broadband noises are hypothesized to mask disruptive noises and improve sleep quality. However, the efficacy of noise to improve sleep measures remains unclear.

The main aim of the study was to quantify sleep quality, sleep fragmentation, sleep latency, and relevant sleep factors by providing broadband noises and to assess whether broadband noise can be a non-pharmacological treatment for better sleep quality. For this purpose, Fitbit Charge 4 and 5 have been used as sleep monitoring devices as well as multiple questionnaires was involved including PSQI, rMEQ, AASP, and St Mary questionnaire. Both hardware and questionnaire data were used to evaluate the effect of white noise on all the sleep factors i.e., sleep stages, duration, and overall sleep score. Also, environmental noise was measured by using decibel meters. Mostly healthy participants having the age of 25.07+/-4.66 for the questionnaire-based study and 24.25+/- 2.57 for hardware-based data were selected for data collection.

Multiple statistical tests have been performed on the collected data. ANOVA tests have been performed on Fitbit's data along with the post-hoc tests. But the results show no significant difference between no noise, sham noise, and white noise data. The same tests were performed on sleep score, total sleep duration, light sleep duration deep sleep duration and REM sleep duration collected by Fitbit, but the results remain non- significant.

Statistical analysis was applied on questionnaire-based data as well. For rMEQ questionnaire, the analysis has been done manually because lesser of the subjects for the analysis. Most of the subjects were neither morning type nor evening type. The chi-square test has been performed on remaining questionnaire-based data.

The chi- square tests applied for comparison between PSQI and AASP. The test was performed to check the correlations between sensory processing patterns and sleep quality measures. The results show that there is no significant difference between the sensory patterns of good and poor sleepers. Chi-square tests were performed on PSQI and St. Mary questionnaire to check the difference between the sleep quality index of good and bad sleepers before and after the noise intervention to check the improvement level. The results show $p = 0.785$ for no noise, $p = 0.763$ for white noise intervention and $p = 0.741$ for the sham intervention for hardware-based subjects. The results for questionnaire based were $p = 0.603$ for no noise, $p = 0.288$ for white noise intervention and $p = 0.126$ for the sham intervention. The results provide p-value>0.05 indicating that there is no significant effect of white noise on good and poor sleepers.

The study is distinguished from previous studies as it claims the results are based on both sleep monitoring devices and questionnaires with proper statistical analysis, having greater sample size and under controlled environmental noise. However, there is room for improvement based on the increasing number of days of data collection. Also, the population of experiment can be changed as white noise might affect infants and patients in ICU rather than healthy individuals.

7.1 Recommendation

Currently, the results are based on healthy students with some having sleep issues. But there is this chance that white noise might affect a specific group of persons, for instance, infants and patients in ICU. Also, some subjects were not comfortable with plain white noise. Maybe some pleasant type of white noise affects the sleep quality of the subjects in a better way. The results may increase its efficacy by increasing number of days of data collection i.e., with and without white noise interventions.

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Appendix A

This appendix provide the links for the Questionnaires used in the research project

Here are the links

1. For PSQI Questionnaire: https://www.sleep.pitt.edu/wp-content/uploads/Study_Instruments_ Measures/PSQI-Instrument.pdf
2. Link for Adult/Adolescent Sensory Profile https://www.pearsonassessments.com/store/usassessments/%20en/Store/Professional-Assessments/Motor-Sensory/Adolescent-Adult-Sensory-Profile/p/100000434.%20Html.html
3. Link for reduced Morningness-Eveningness questionnaire https://www.tandfonline.com/doi/full/10. 1080/07420528.2018.1564322
4. Link for St. Mary Sleep questionnaire https://pubmed.ncbi.nlm.nih.gov/7232974/