Direct detection of REM sleep using low-cost cameras: The ZZZleep Mask

Choi, Sarah, 12th, sarahchoi23@fsha.org, Flintridge Sacred Heart Academy
Park, Kana, 12th, kanapark23@fsha.org, Flintridge Sacred Heart Academy
Senthil, Kirthana, 12th, kirthanasenthil23@fsha.org, Flintridge Sacred Heart Academy
Advisor Ty Buxman, tbuxman@fsha.org

Abstract:

Students need adequate sleep in order to maintain their highest academic potential. Inadequate sleep, specifically Rapid Eye Movement (REM) sleep, can result in focus loss and inattention, which can be detrimental to brain development and function in adolescents. A sleep mask (The ZZZleep Mask) has been developed to directly track REM sleep cycles using an infrared-sensitive camera and integrated tracking software. The ZZZleep Mask system can successfully collect data and detect eye motion.

1.0 Introduction

High school students are commonly sleep deprived due to early school start times and academic workload (Mateika, 2002). Many young people do not get the recommended amount of sleep, with 72.7% of high school students getting less than the recommended amount of sleep for their age (Sleep Foundation, 2021). In the classroom environment, sleep-deprived students can consistently enter microsleep (periods of sleep for a few seconds) and miss academic lessons or lose focus altogether. The consequences of sleep deprivation and daytime sleepiness are especially problematic for college students and can result in compromised learning and an increased risk of academic failure (National Library of Medicine, 2014).

1.1 Background

Sleep is divided into four phases or stages (see Figure 1), and typical teenagers should complete 4-6 cycles of these sleep stages each night. Stages I through III can be categorized as Non-REM (NREM) sleep stages (Sleep Foundation, 2022). These first stages collectively last 90 minutes per cycle. While all sleep stages are counted as accumulated sleep time, REM is the most significant yet hardest to achieve since a person must pass through each stage sequentially. (Cleveland Clinic, 2021).

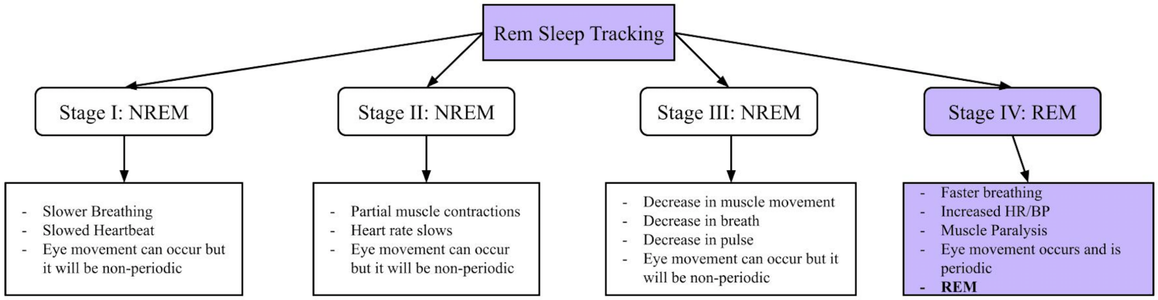

Figure 1: Sleep Stages and Characteristics of Each Stage

The REM (Rapid Eye Movement) stage is characterized by the eye oscillating an average of 15.9 times per minute (Takahashi & Atsumi, 1997). The eye moves back and forth underneath the eyelid, and the protrusion of the cornea is visible as a bump in the eyelid. During NREM sleep, the eye also moves, but at a much slower and non-periodic rate. Eye movement gradually slows from Stage I to Stage III (Pacheco & Singh, 2022). Stage I initially begins at 4 oscillations per minute, and Stage III ends with close to 0 oscillations, only for REM sleep to increase the speed again (Andrillon et al., 2015).

1.1.1 REM and Cognitive Function

The average person needs a minimum of 4 REM cycles to sufficiently recuperate from the day and receive the benefits of REM sleep (Sleep Foundation, 2016). While four to six REM cycles are recommended, waking up at the end of one cycle feels better than waking up in the middle of any stage (The Sleep Foundation, 2016). Since REM sleep has a direct correlation with a person who doesn't meet these recommendations, it can lead to deterioration in cognitive function. Cognitive function is the way the brain processes new information, solves problems, and makes decisions. Cognitive function has a significant impact on everyday behavior and tasks. REM sleep deprivation can lead to both short-term and long-lasting consequences.

Short-Term Impacts	Long-Term Impacts
● Memory loss ● Loss of motor skills ● Cannot comprehend and resolve day-to-day situations (Sleep Foundation, 2016) ● Riskier choices/mood swings ● Reduced attention span ● Almost like in a drunken state (Sleep Foundation, 2016) ● Microsleep and sleep delay from shifting schedules (Mateika, 2002)	● Weakened immune system (National Sleep Foundation, 2020) ○ Deeper pain ○ Blocked growth of healthy tissue and cells ● Sleep disorders like insomnia, obstructive sleep apnea, and Alzheimer's dementia (Sleep Foundation, 2016) ● Altered circadian rhythm (Walker 2020)

Table 1: Impact on Cognitive Function From Not Receiving Enough REM Cycles

1.2 Comparison of REM Detection Methods

The current most accurate sleep test is polysomnography (PSG), considered the gold standard of sleep tracking (Rundo & Downey, 2019). Polysomnography uses a combination of measurements, including electroencephalograms (EEG), breathing and cardiac rate, blood oxygen level, and eye and leg movements to track how often a participant falls into REM sleep (Mayo Clinic, 2020). An EEG uses electrodes to measure brain electrical activity and note when the brain waves signify REM (Mayo Clinic, 2020). When conducting a study that uses PSG, the sensors can cause skin irritation, and the wires and machinery often interfere with quality sleep. Sleep studies using PSG are commonly administered at sleep-tracking facilities. While at-home versions are available, they only utilize a subset of the tracking sensors (cardiac and respiratory), which decreases accuracy (Mayo Clinic, 2020).

Another sleep test technology is heat tracking. Infrared sensors track body temperature as it decreases in NREM and increases in REM (Hopkins Medicine, 2021). A third technology uses force sensors to directly track the motion the eyes create when they move back and forth, counting the number of oscillations. However, this type of technology could cause irritation due to direct contact with the eye. Finally, cameras used to image the eye can provide direct, non-contact tracking.

A popular device people use to track REM sleep are fitness trackers such as Fitbits. Fitbits in particular use heart sensors to detect REM and have a sleep app that uses a machine learning algorithm to analyze a person's sleeping patterns. Research has shown that Fitbits don't accurately measure transitions between sleep stages when there are more transitions between sleep stages, therefore making the Fitbit an unreliable method to track REM sleep (Saleh, 2020).

	Description	Direct	Indirect	Contact	Non-Contact
PSG	Uses EEG electrodes, respiration, cardiac effects, eye movement, leg movement	+	+	+	
Thermal	Uses infrared sensors to track temperature changes		+		+
Force	Uses force sensors to detect eye movement	+		+	
Camera	Uses a camera to track eye movement	+			+
Fitbits	Uses heart rate sensor to detect REM		+	+	

Table 2: Current Methods of Sleep Tracking and REM Detection

1.2.1 Infrared (IR) Safety

The ZZZleep Mask's use of infrared light may be a cause for concern. Hazards include cataracts, heat absorption leading to intense burns, and light absorption leading to damaged retinas. However, these dangers come with a huge burst of IR radiation in a moment or adequate amounts of IR radiation over a period of time (Ramsay, 2021). In terms of thermal IR radiation, direct contact with the skin can elevate temperature by 10˚C. Non-contact, direct focus could result in a .5˚C increase (Bozkurt & Onaral, 2004). The ZZZleep Mask's non-contact IR design reduces the risk and does not compromise the user's safety with heat. In terms of IR light absorption, an IR LED would need to be placed about 8.5 mm away from the eye in order to meet the 10 mW/cm^2 safety limit (Ramsay, 2021). The ZZZleep Mask's IR light is about 4 cm away from the edge of the user's eye, or about 40 mm away. Additionally, the light does not shine directly onto the eye, instead coming at an angle that could not hit the retina if the eye opened. Overall, IR light is safe to use on an eye (Kourkoumelis & Tzaphlidou, 2011) and the ZZZleep Mask increases safety with no contact to the eye.

1.3 Marketed Products and Prototypes

While polysomnography is the most accurate way to track sleep quality and Fitbits are the most accessible way, other methods are on the market.

Researchers at MIT used simpler sensors (force sensors) than the ones usually used to detect REM Sleep such as EEGs in order to develop a comfortable sleep mask called MASCA. They were given technology from researchers involved in the 1990s Harvard Nightcap project. Both projects were similar in concept, but MASCA furthered Nightcap's progress (Horowitz et al., 2021). The researchers' idea behind creating the sleep mask is revolutionary; however, the execution of both masks fell short.

One project from Pomona College has already used IR lights and non-Raspberry Pi IR sensors to track REM sleep (Kelsey & Solitis, 2011). IR detectors suspended over the eyes measured the amount of infrared light the eyes reflected back while oscillating. The data was analyzed through a software algorithm that used a method called Seismic Detection. Seismic Detection took averages of the eye movement data and compared them as ratios to establish a threshold that represented whether or not a user was in REM. Additionally, a REM Sleep Alarm was developed using the analysis to wake the user up when REM Sleep was detected. The Pomona mask ended with a prototype that analyzed a user's eye movement data to detect REM and a REM Sleep Alarm that alerts a user to wake up when REM Sleep was detected. However, the Pomona mask was uncomfortable and had a low to average REM detection accuracy. The ZZZleep Mask utilizes this research, prioritizing comfortabilty and a more accurate way of detecting REM. Unlike the Pomona Mask, the ZZZleep Mask instead pairs infrared lights with an infrared detecting camera to increase accuracy in detecting REM.

1.4 Project Statement

High school students need high-quality sleep defined by a minimum of 4 uninterrupted REM cycles in order to support high academic performance. By developing a portable sleep mask, The ZZZleep Mask, that can detect and record REM sleep cycles and durations, students could be made aware of their sleep patterns and receive recommendations to improve their overall sleep. This REM sleep tracker would recommend sleeping at an earlier or later time to either get another REM phase in or finish one that was cut off. This will allow students to obtain the recommended hours of sleep per their age group in order to achieve their goals of maintaining their highest academic potential in an educational setting.

2.0 Methods Overview

The development of a portable, REM-detecting sleep mask is described. The ZZZleep Mask can distinguish between rapid eye movement and slow eye oscillation, or irregular oscillation, found in NREM stages. A Raspberry Pi NoIR camera was placed above the eye (along with infrared lights to illuminate the eye) to capture images throughout the night, and software analyzes these images to identify REM stages.

2.1 Specifications

In REM sleep, a person’s eye oscillates an average of 15 times per minute, or once every four seconds. One oscillation is a complete left-to-right movement. A photo taken every two seconds can capture the eye facing a different direction.

The camera must be able to capture photos in the dark with clear quality. The Raspberry Pi NoIR camera can achieve this requirement (Raspberry Pi Ltd, 2016) with external infrared illumination. These lights are invisible to the human eye and do not disturb individuals while they sleep. In order to ensure the user acquires comfortable sleep, the camera and lights do not touch the user.

In addition, since the mask must be comfortable to wear during sleep, low weight is an important factor. The camera and IR light source need to be adjustable as people's faces are shaped differently, and the camera must be stable to ensure clear data recording.

2.1.1 Hardware

The ZZZleep Mask requires the ability to detect the motion of the eye under a closed eyelid in the dark. To achieve this, an IR LED will illuminate the eyelid while an IR-sensitive camera takes pictures of the lid from the front of the eye. Image software will detect differences in brightness based on shadows cast by the “cornea bump” (see Figures 2 and 3).

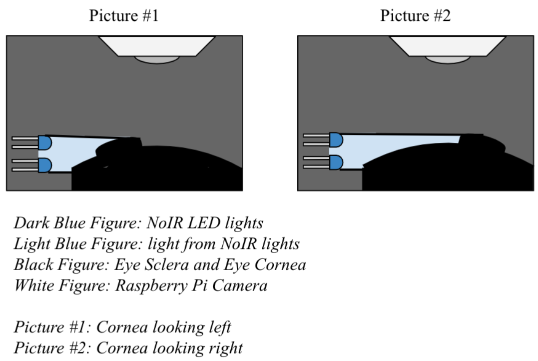

Figure 2: Side View of Light Hitting Closed Eye While Looking in Different Directions

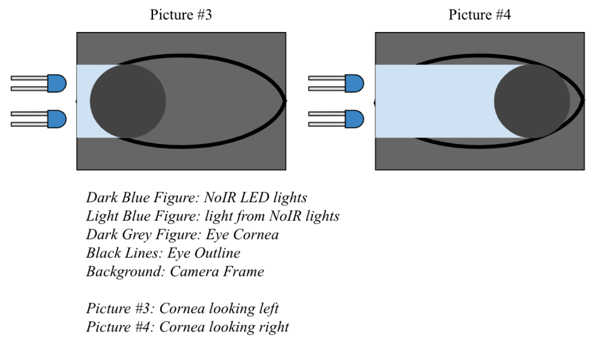

Figure 3: Top View of Light Hitting Closed Eye While Looking in Different Directions

To fix the camera and lights onto the mask, the first prototype involved what every good thing starts with: duct tape and a dream. Prototype 2 involved a ski mask, wire, and magnets to allow camera and light adjustment. Finally, the current prototype (see section 3.1) is a 3D-printed mask with adjustable settings. A 3D-printed pan-tilt stage is built into the side of the mask using two screws to alter the light's angle and height for easy adjustment. The camera is attached to the inside of the mask using magnets glued to the back of the 3D-printed camera holder and magnet wallpaper. Repeatable adjustments are important to allow for varied facial measurements. The ZZZleep Mask frame is lined with foam for comfort and is attached to the user's head with a comfortable knit elastic band.

The camera must be placed directly above the eye when it is open with the cornea in the center of the screen. When the eye is closed, the majority of the eyelid should be visible. The closed eye slit should barely line the edge of the camera.

2.1.2 Software

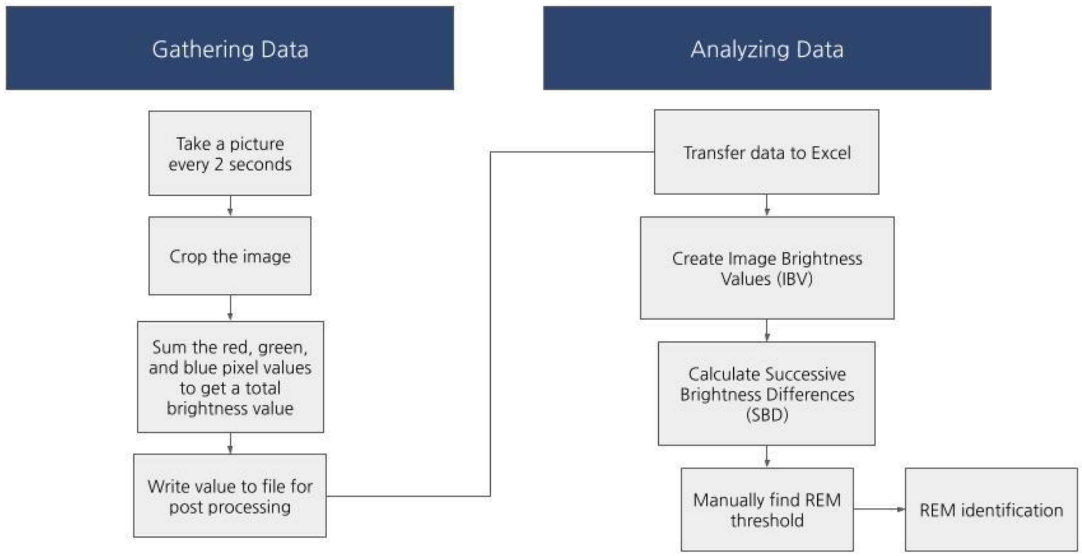

Figure 4: REM Software Integration and Analysis Flowchart

The LED placement and calibration are important because the software detects eye motion from brightness changes based on reflections of the IR LED light. These light reflections change based on the eye's direction. The images were cropped so that the algorithm could effectively calculate the Image Brightness Value (IBV) of only the illuminated eye. The raspberry pi takes a succession of closed-eye images every two seconds. Image Brightness Values (IBV) are calculated for each image and the brightness change for consecutive images, the Successive Brightness Differences (SBD), is calculated. If the first IBV is A and the second IBV is B, the first SBD can be calculated as B – A. The second SBD was C – B and so on. This SBD can be used to detect when the user began and ended a REM phase.

2.2 Validation: System

A simulated sleep cycle was used to make sure that the entire system worked together effectively. System validation ranged from 5- to 25-minute simulated cycles with periodic REM phases. For example, in a 5-minute test, the person wearing the mask would switch between keeping their eye still and oscillating the recommended amount every minute. For the 20- and 25-minute simulated cycles, the user would switch every five minutes. This simulation of REM sleep will show that the software can differentiate between REM and NREM eye motion.

3.0 Results

3.1 Hardware Prototype

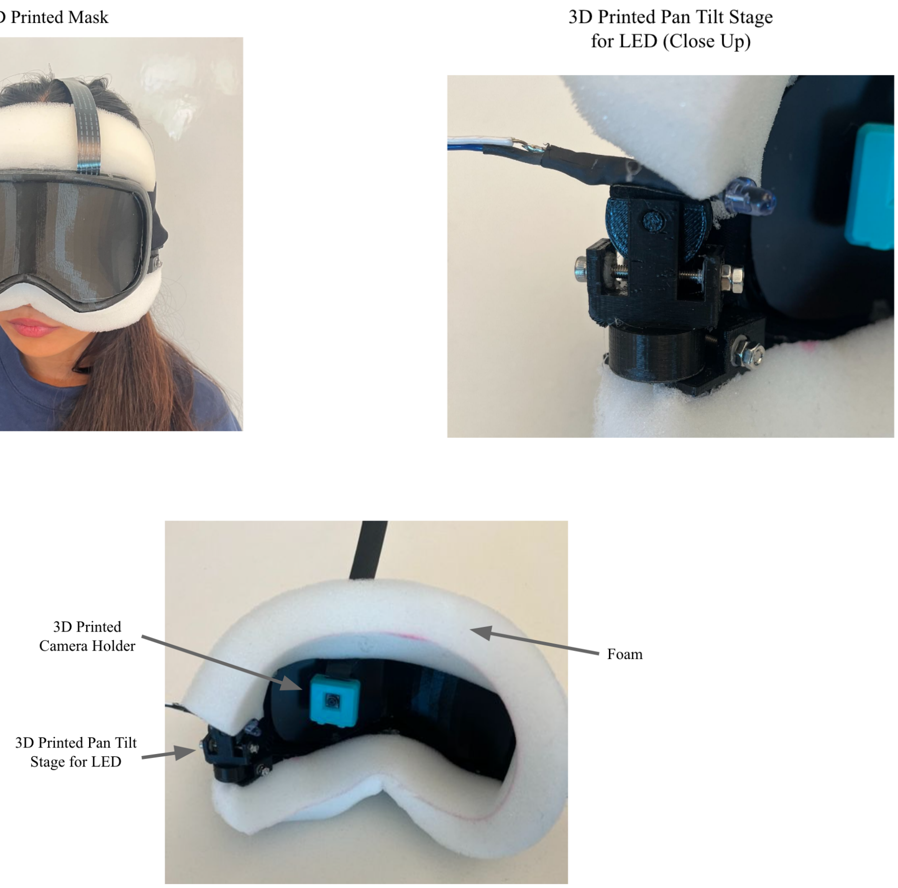

Figure 5: Mask Hardware Prototype (Labeled)

3.2 Sleep Tests

For the 5-minute simulated REM/NREM sleep cycle test, IBV and SBD are graphed in Figures 6 and 7.

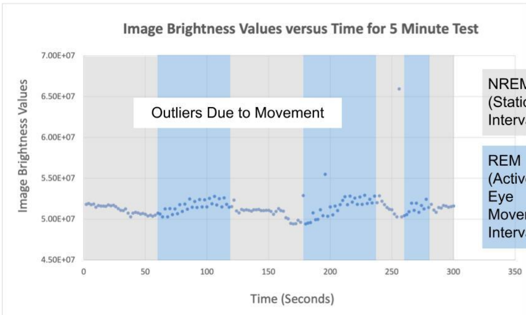

Figure 6: 5-Minute Test for Image Brightness Values (IBV) with Intermittent Periods of Simulated REM

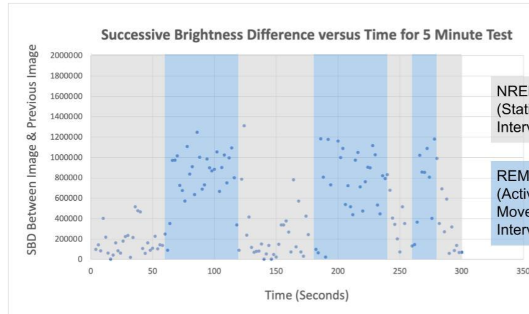

Figure 7: 5-Minute Test for Successive Brightness Differences (SBD) with Intermittent Periods of Simulated REM

As can be seen in Figure 6, during simulated REM intervals, the IBV is not constant. Figure 7 plots the IBV difference between successive images. As can be seen, the SBD during simulated REM is noticeably higher than during simulated NREM. These SBD values can be used to detect REM onset and termination.

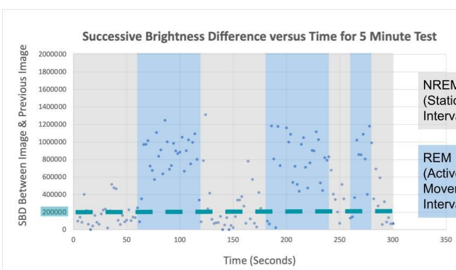

Figure 8: User #1's 5-Minute Sleep Test with a 200,000 REM Threshold

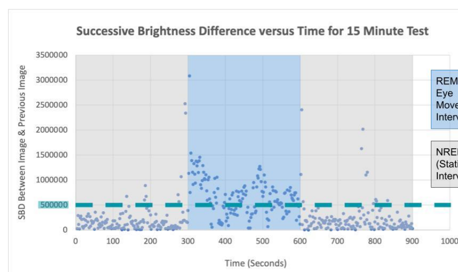

Figure 9: User #2's 15-Minute Sleep Test with a 50,000 REM Threshold

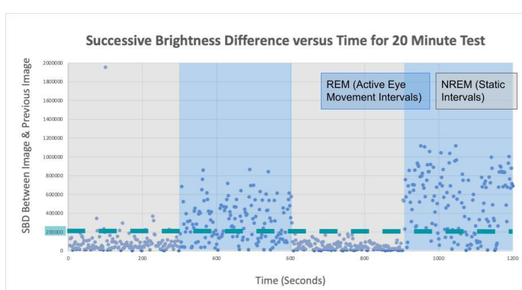

Figure 10: User #3's 20-Minute Sleep Test with a 200,000 REM Threshold

Three users' results are presented in Figures 8, 9, and 10. Each user has a different threshold for when REM begins, as indicated by the green dashed line in the Figures below.

4.0 Discussion

A simulated REM cycle was evaluated by a user wearing the ZZZleep Mask and undergoing a test that required them to move their eyes at specific times. Further development of The ZZZleep Mask to allow for in-site sleep testing will provide a more complete validation of the mask's ability to detect REM onset. Current validation from the results of the multiuser 5, 15, and 20-minute sleep tests indicates the need for a calibration phase. Each test had a different threshold for when the SBD began indicating REM sleep. The ZZZleep mask would need to find the threshold of each individual rather than having a set number for everyone. Individualization includes differentiating between the NREM and REM eye oscillations. The most important work that has not been done is on slower, non-periodic NREM motion. NREM was not taken into consideration during testing. The mask must be able to differentiate between NREM and REM motion. Other factors to consider are if the user wakes up at night and/or opens their eyes, the flexibility of the mask, and the adjustability limits for the camera and lights. The process should be automated so that the user only needs to press a button or hit Start." Automation should lead to an application that suggests when a user should either go to bed or wake up. At-home testing should allow for easily accessible mask portability. By individualizing the mask per user, it can track each person's unique REM pattern. It can then give recommendations that benefit the user rather than a generalized statement that may not help.

5.0 Conclusion

People, specifically high school students, need a way to get better quality sleep. Getting enough REM sleep promotes better health and provides the quality sleep people need. A viable sleep mask prototype has been created to detect the REM sleep stages. The 3D-printed ZZZleep mask includes an adjustable IR LED powered by two batteries on the top of the mask. The camera is held up by a magnetic sheet on the inside of the mask. Foam surrounds the edge of the mask and a 2" knit elastic is used as the mask's band. The software can capture brightness values that can tell when the eye is pointing left, right, or straight. The SBD method is a viable method to detect average REM oscillation frequency. The project comes at a low cost and is a non-contact, direct form of REM measurement. Although PSG remains the most accurate sleep-tracking method, this mask could potentially replace all at-home tests due to its higher accuracy and comfortability.

5.1 Acknowledgements

We would like to acknowledge and thank our academic advisors Ty Buxman and Bruce Waggoner who provided us with the opportunity to do this engineering research. Without this class and their guidance, we would not be able to pursue a STEM education intensive as now. We would also like to forward this gratitude to our school and its STEM program for allowing us this opportunity as women and high school students.We thank Alyssa Adriano and Hannah Huynh for their previous work on creating a portable REM tracker. We value their research and the foundation they provided us for our project. We would also like to acknowledge the AP Computer Science curriculum, Thingiverse, and Amazon.

6.0 References

Andrillon, T., Nir, Y., Cirelli, C. et al. *Single-neuron activity and eye movements during human REM sleep and awake vision*. Nat Commun 6, 7884 (2015). https://doi.org/10.1038/ncomms8884

bigleyj. (2021, December 3). *Sleep: How Much You Need and Its 4 Stages*. Cleveland Clinic; Cleveland Clinic. https://health.clevelandclinic.org/your-complete-guide-to-sleep/

Bozkurt, A., & Onaral, B. (2004). *Safety assessment of near infrared light emitting diodes for diffuse optical measurements*. BioMedical Engineering OnLine, 3(1). https://doi.org/10.1186/1475-925x-3-9

Do Sleep Trackers Really Work? (2021, August 8). Hopkinsmedicine.org. https://www.hopkinsmedicine.org/health/wellness-and-prevention/do-sleep-trackers-really-work

Hershner, S. D., & Chervin, R. D. (2014, June 23). Causes and consequences of sleepiness among college students. Nature and science of sleep. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4075951/

Horowitz, A. H., Rosello, O., Vega, T. et al. (2021). *Masca: A Flexible Sleep Mask for Rapid Eye Movement (REM) Detection and Electrical Muscle Stimulation (EMS) Intervention*. MIT Media Lab. https://ethanweber.me/sleep/Human_2_0_Paper.pdf

How Is Sleep Different for Men and Women? | Sleep Foundation, 26 Oct. 2018, www.sleepfoundation.org/how-sleep-works/how-is-sleep-different-for-men-and-women.

https://www.facebook.com/WebMD. *What Are REM and Non-REM Sleep*? WebMD, WebMD, 26 Apr. 2005, www.webmd.com/sleep-disorders/sleep-101.

How Lack of Sleep Impacts Cognitive Performance and Focus | Sleep Foundation. (2016, November 14). Sleep Foundation. https://www.sleepfoundation.org/sleep-deprivation/lack-of-sleep-and-cognitive-impairment

Kahn, Jeff. *How Much REM Sleep Do You Need? PSA: You Don't Need to Know*. Risescience.com, 2019, www.risescience.com/blog/how-much-rem-sleep-do-you-need.

Kelsey, S., & Soltis, B. (2011, June 6). Rem sleep alarm. DigitalCommons@CalPoly. https://digitalcommons.calpoly.edu/eesp/73/

Kourkoumelis N, Tzaphlidou M. Eye safety related to near infrared radiation exposure to biometric devices. ScientificWorldJournal. 2011 Mar 1;11:520-8. doi: 10.1100/tsw.2011.52. PMID: 21380486; PMCID: PMC5720004.

Mateika, J. H. (2002, June). The Impacts of Sleeping on Learning and Behavior in Adolescents. ResearchGate. Retrieved September 27, 2022, from Georgios Mitru, et al. ResearchGate, Blackwell Publishing, June 2002, www.researchgate.net/publication/237808777_The_Impact_of_Sleep_on_Learning_and_Behavior_in_Adolescents.

Murray, M. (2019, January 25). *Raspberry Pi NOIR vs Normal Camera*. The Geek Pub. https://www.thegeekpub.com/16220/raspberry-pi-noir-vs-normal-camera/

National Sleep Foundation, Nov. 2020, www.thensf.org/what-is-rem-sleep/.

Pacheco, Danielle & Singh, Abhinav. *What Happens During NREM Sleep*? | Sleep Foundation. (2022, July 8). Sleep Foundation. https://www.sleepfoundation.org/stages-of-sleep/nrem-sleep

Polysomnography (sleep study) - Mayo Clinic. (2020). Mayoclinic.org; https://www.mayoclinic.org/tests-procedures/polysomnography/about/pac-20394877#

Ramsay, D. (2021, April 8). How to Tell if your Eye-Tracking IR Diode is Safe. Epistemology, Cognition, and the Future of Technology. https://blog.davidbramsay.com/how-to-tell-if-your-eye-tracking-ir-diode-is-safe/

Raspberry Pi Documentation - *Camera*. (2013). Raspberrypi.com. https://www.raspberrypi.com/documentation/accessories/camera.html

Raspberry Pi Ltd. (2016). *Buy a Raspberry Pi Camera Module 2 – Raspberry Pi*. Raspberry Pi. https://www.raspberrypi.com/products/camera-module-v2/

Raspberry Pi Ltd. (2016). *Buy a Raspberry Pi Camera Module 2 NoIR – Raspberry Pi*. Raspberry Pi. https://www.raspberrypi.com/products/pi-noir-camera-v2/

Rundo, J. V., & Downey, R., 3rd (2019). *Polysomnography*. Handbook of clinical neurology, 160, 381–392. https://doi.org/10.1016/B978-0-444-64032-1.00025-4

Rusch, H. L. (2020, December 17). Links between stress, sleep, and inflammation: a translational perspective of resilience. ResearchGate; unknown. https://www.researchgate.net/publication/347984977_Links_between_stress_sleep_and_inflammation_a_translational_perspective_of_resilience

Saleh, M. (2020, October). How accurate is Fitbit sleep? | Top Picks | Medical News Bulletin. Medical News Bulletin. https://medicalnewsbulletin.com/how-accurate-is-fitbit-sleep/

Stickgold, R., Pace-Schott, E., & Hobson, J. Allan. (1994). *A New Paradigm for Dream Research: Mentation Reports Following Spontaneous Arousal from REM and NREM Sleep Recorded in a Home Setting*. Consciousness and Cognition, 3(1), 16–29. https://doi.org/10.1006/ccog.1994.1002

Suni, E. (2022, October 7). Stages of sleep. Sleep Foundation. Retrieved December 9, 2022, from https://www.sleepfoundation.org/stages-of-sleep

Suni, E. (2023, April 4) *100+ Sleep Statistics - Facts and Data About Sleep 2023* | Sleep Foundation. (2023, April 4). Sleep Foundation. https://www.sleepfoundation.org/how-sleep-works/sleep-facts-statistics.

Takahashi, Kazumi, and Yoshikata Atsumi. *Precise Measurement of Individual Rapid Eye Movements in REM Sleep of Humans*. Sleep, vol. 20, no. 9, Sept. 1997, pp. 743–52, https://doi.org/10.1093/sleep/20.9.743.

Walker, W. H., Walton, J. C., DeVries, A. C., & Nelson, R. J. (2020). *Circadian rhythm disruption and mental health*. Translational Psychiatry, 10(1). https://doi.org/10.1038/s41398-020-0694-0

7.0 Appendices

Raspberry Pi Final Code , Code_Appendix