Detecting REM Sleep Cycles Using Low Cost Cameras

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Submitted for publication: 5/30/2021

Abstract

Sleep deprivation affects millions of adolescents, taking a toll on both their physical and mental health. More specifically, the damaging aspect of lack of sleep is the lack of REM (rapid eye movement) sleep, a stage of sleep that is crucial in the development of the brain. Existing methods used to track sleep are reviewed and a method to use a camera to detect and report REM sleep cycles at home is developed. Finally, a description of the outstanding barriers to a full working prototype are provided along with a plan for completion.

1.0 Introduction

According to the CDC, an overwhelming 72.7% of high school students are not sleeping the recommended minimum of 9 hours each night (Wheaton, 2018). Although teenagers may think sleep deprivation merely causes inconvenient drowsiness, insufficient sleep can cause serious negative short-term and long-term consequences on mental and physical health. For instance, sleep deprivation increases chances of depression fourfold and has been associated with cardiovascular disease, obesity, and type 2 diabetes (The Impact of Sleep on Teen Mental Health, 2017). Furthermore, lack of sleep hinders the development of the prefrontal cortex, a part of the brain that performs daily tasks, makes decisions, forms a personality, and moderates social behavior (Hathaway & Newton, 2020).

1.1 Background

Sleep is divided into four stages, which include three stages of non-REM sleep and one stage of REM, or rapid eye movement, sleep (Figure 1).

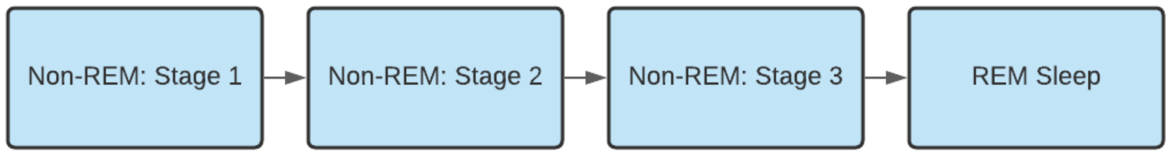

Figure 1: Sleep Stages

The first three stages (non-REM) are when physical restoration of the body occurs (5 Wonders of Restorative Sleep, 2020). The first stage of sleep begins within minutes of falling asleep. During these stages of non-REM sleep, the body transitions from light sleep to deep sleep. After non-REM, a person enters the fourth stage, REM.

1.1.1 REM

REM is the stage of sleep that is mentally restorative, allowing the brain to develop (The Impact of Sleep on Teen Mental Health, 2017). A lack of REM sleep has been shown to lead to delayed development of the prefrontal cortex (Muzur, Pace-Schott, Hobson, 2002). The development of a teenager's prefrontal cortex includes the formation of the teen's decision making skills, personality, and ability to complete daily tasks. Moreover, without enough REM cycles, it becomes harder for people to concentrate, regulate their emotions, and cope with difficult situations. (Hathaway & Newton, 2020). Because the prefrontal cortex is such a vital part of functioning in daily life, it is important that teenagers sleep for at least nine hours, or six complete REM cycles, each night to allow the prefrontal cortex to fully develop over the course of one's teenage years (Crane, 2016).

REM sleep is characterized by the eye oscillating at about 16 times per minute (Takahashi & Atsumi, 1997), which is visible through the closed eyelid. Teenagers should obtain 6 full REM cycles per night, with the first cycle lasting about 10 minutes and the last one lasting up to 60 minutes (Felson, 2020).

1.1.2 Image Detection

Image detection is processing images using computer technology to detect objects. Recently, camera and image-processing algorithms have been used to detect the location of an eye's pupil in an attempt to detect aging (Marandi & Gazerani, 2019). For video-based eye trackers, "goggles, head-mounted, desktop-mounted and remote devices" are all commercially available (Marandi & Gazerani, 2019). Additionally, image detection on the eye has been used to track attention span (Valliappan et al., 2020). However, a difficulty in image tracking is that the object being detected cannot be the same color as the predominant color in the fixed image (Daciu & Szekely, 2009), which may create complications in tracking REM with the eye closed since the color is mostly the same throughout the image. Because the rapid eye movement that occurs during REM sleep is visible through the eyelid, image detection can be used to detect REM using cameras and software.

1.2 REM Detection Methods

The measurement of sleep must include both the quantity and quality of sleep. The quality of a person's sleep is measured through the length and number of REM cycles completed during sleep. Some of the current methods that are used to detect REM sleep either require extensive equipment or are inaccurate in their detection of REM. Table 1 summarizes three key methods that informed our project.

Table 1: Sleep-Tracking Methods Summarized

Methods	Pros	Cons
Polysomnography	Accurate	Uncomfortable; excessive equipment needed
Wrist Actigraphy	Comfortable	Inaccurate
Microphone Tracking	Unobtrusive	Satisfactory in accuracy; advanced technology required

1.2.1 Polysomnography

The most reliable technique used to detect REM is visiting a sleep study facility, where the patient's sleep is monitored using polysomnography, a combination of electroencephalogram (EEG), electrocardiography (ECG), electrooculography (EOG), and electromyography (EMG), which all measure the electrical output of the body's activity, specifically electrical signals from the brain, heart, eyes and muscles. These sensors are used to identify a person's sleep stages and changes in sleeping patterns. This method utilizes sensors, which measure the electrical activity in specific organs, that are attached to the head and body with adhesive and connected to a nearby monitor, which can be irritable for the person being studied. Polysomnography has proven to be very accurate in detecting REM sleep because it measures brain waves, the oxygen level in a person's blood, heart rate and breathing, as well as eye and leg movements (Mayo Clinic Staff, n.d.).

1.2.2 Wrist Actigraphy

Wrist actigraphy detects REM using a device attached to the wrist, like the widely popular Apple Watch and FitBit. These devices use limb movement and heart rate to detect changes in a person's sleeping patterns (Chapa-Martell & Liang, 2019). Actigraphy devices are traditionally used to assess long-term sleep quality, differentiating between sleep time, sleep efficiency, and instances of being awake after sleep onset (Herscovici, Pe'er, Papyan, & Lavie, 2006). These devices are wireless, portable, and are able to be worn in free-living environments (Herscovici, Pe'er, Papyan, & Lavie, 2006). However, while these devices are easily available for the layperson, the detection of REM has been shown to be inaccurate using wrist actigraphy and has been shown to be even more inaccurate if the person using the device has low sleep efficiency, meaning that the percentage of time spent asleep while in bed is below 85% (Herscovici, Pe'er, Papyan, & Lavie, 2006).

1.2.3 Microphone Tracking

The use of a microphone to track REM cycles was introduced by a research group that recorded the sound of a person sleeping to analyze when a person was in REM. During REM, breathing rate increases, which was detected by the microphone device (Zhang et al., 2017). Zhang et al. mentioned that most sleep monitors are obtrusive as they often require users to wear an uncomfortable device while sleeping (Zhang et al., 2017). The researchers used the microphone on a recording pen to detect light, deep, and REM sleep. However, a significant factor in this study was eliminating background noise when recording a person's sleep session, which requires advanced technology.

1.2.4 Assessment of IR safety

According to the IEC [International Electrotechnical Commission] standards, "IR light at a wavelength of 850 nm light should not exceed 10 mW/cm^2 if exposure time will exceed 1000 seconds to be considered safe" (Iovine, 2020). Any use of infrared light must meet this safety standard to prevent causing damage to the subject's eye(s).

1.3 Problem Statement

Current methods used to detect REM sleep are inaccurate or not easily accessible. Providing access to accurate data about REM sleep patterns has potential to affect teenagers' choices about sleep routines. This project will utilize low cost cameras to detect changes in eye position during sleep. Software will be developed to measure the frequency of eye oscillation (which characterizes the REM stage of sleep), the length of each REM cycle, and the total number of REM cycles in a night. This information will be presented to the user with recommendations for behavioral changes that could improve the quality of their sleep.

2.0 Methods

Eye movement can be seen through a closed eye based on the changing shape of the eyelid. During REM sleep, the eye oscillating at an average of 15.9 times per minute (Takahashi & Atsumi, 1997) is detectable by visual inspection, and therefore also by video recording and image analysis.

2.1 Image Acquisition

A Raspberry Pi Camera Module v2 was used to capture images of the eye. Image collection in the dark (during sleep) requires artificial lighting that can illuminate the eye but not disturb the subject (an 850nm IR flashlight is used for this purpose).

2.2 Image Processing

2.2.1 Finding an algorithm

Four different algorithms for processing images were investigated to find a method for detecting changes in eye placement (whether the eye is looking left or right). The first two algorithms used, template matching and image registration, were taken from scikit-image, an open-source library for processing images in the Python programming language. In template matching, an image patch is identified in a larger image. In image registration, the relative shift between two different images is calculated by the program, providing the number of pixels shifted as the output. The third algorithm, centroid detection, used a combination of original code and pre-existing code (Finding the center of mass in an image, 2018) to calculate the weighted center of brightness from grayscale eye images. The fourth algorithm divided an image into a left and right side, calculating the total brightness of each side. The brightness algorithm was utilized to detect eye placement for our project since the results were the most accurate compared to the other algorithms tested. Developing an algorithm to determine the position of the closed eye is a vital part in starting the larger process of detecting REM sleep using cameras.

2.2.2 Brightness algorithm

The algorithm used for this project, to determine whether a closed eye is looking left or right, was the brightness method. Each individual image of an eye is manually cropped, with the eye roughly in the center. This newly cropped image is split in half vertically. The picture is converted into a 2D array to allow the program to calculate the brightness values of each pixel. Each pixel has a brightness value ranging from 0 to 255. The brightness values of the pixels in each half of the image are added up. The sum of the brightness values in each half of the image is converted into a percentage of the summation of the brightness values in the entire image. These percentages for each half of every image is output by the program. Using either only the left half or the right half of every image, the percentages are then compared to see if there is a change in the brightness which corresponds to the position of the eye. If the output between each image changes only by a few percent, it can indicate a change in the direction the eye is looking.

2.3 Hardware

A mask device was created to hold the low-cost camera and infrared flashlight in the optimal position.

A first iteration of the mask was created using a cereal box (Figure 2). The raspberry pi was placed on the top of the cereal box with the camera extending inside the mask through a small hole. The camera extended approximately 3.5 inches from the user's eye, depending on where the mask was placed. The infrared flashlight was then placed at various distances from the user's eye inside the mask. These placements included both the left and right sides of the mask, the back left and right corners, and the middle back of the mask. It was discovered that the placement to get the best lighting in the image of the eye was for the IR flashlight to be placed directly next to the raspberry pi camera for this prototype.

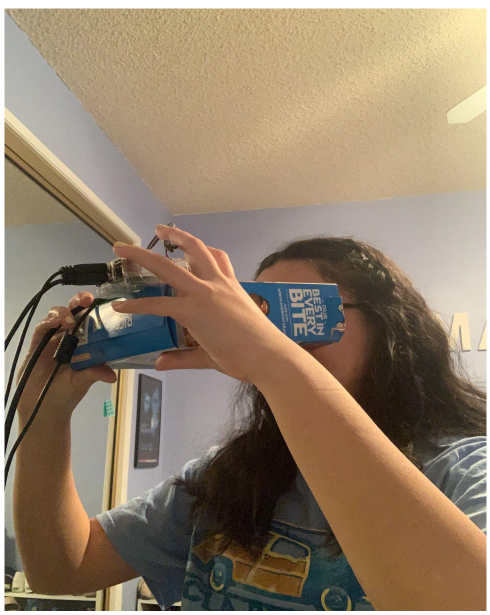

Figure 2: Mask Iteration 1

Infrared LEDs were also tested as a source of lighting, using a small breadboard, attached inside the cereal box to the back wall. Three LEDs were used with various resistor strengths;

however, in all circumstances tested, the LEDs did not provide sufficient lighting for the raspberry pi camera.

A second iteration of the mask was then created using a matboard and a laser cutter (Figure 3). This iteration consisted of five pieces of matboard taped together to form the mask. The front piece being 3 x 6.5 in, the side pieces being 3 x 4.5 inches, the top piece being 6.5 x 2 inches, and the bottom piece being 6.5 x 2.75 inches. The bottom piece was also constructed with a half-moon cutout to account for the user's nose when placed on the user's face.

Figure 3: Mask Iteration 2

3.0 Results

Using the data from the left half of each image, the brightness algorithm had an accuracy of 70% identifying the correct eye position. Using a sample of 10 images, the output of this data set was plotted onto a graph (Figure 4). The blue dots represent images of the eye looking left, and the red dots represent the images of the eye looking right. The value of the eye looking left was usually lower than that of the eye looking right. The plotted points should be above or below the yellow line shown in the graph, which was chosen to maximize the accuracy of the results. Since ⅗ of the blue dots were under the line and ⅘ of the red dots were above the line, the results came out to be 70% accurate. With more time, new algorithms or better pictures could improve the accuracy of detecting where the eye is looking.

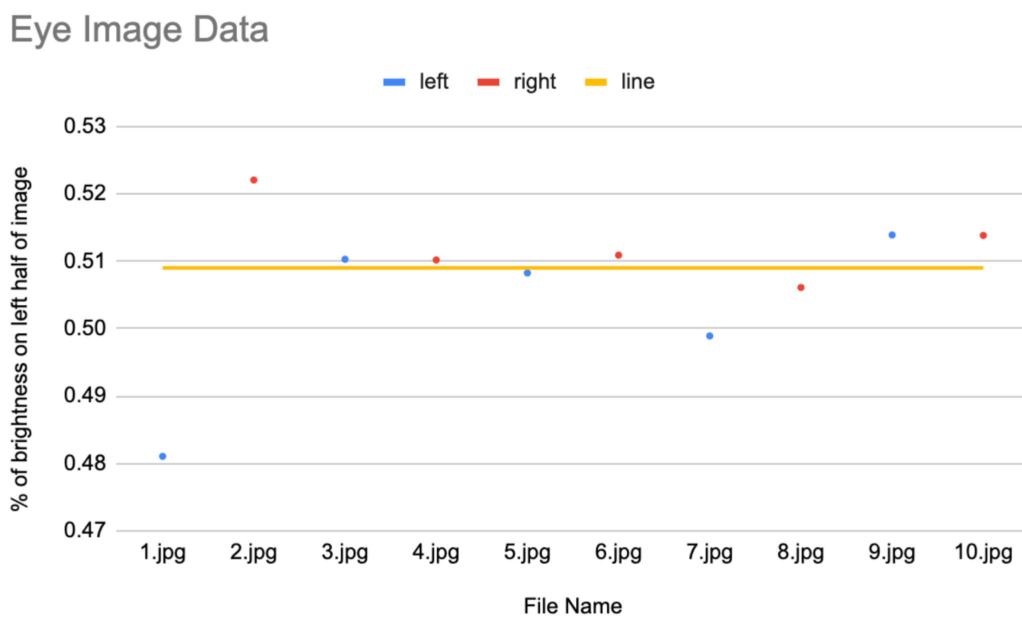

Figure 4: Brightness Algorithm Results

4.0 Discussion

4.1 Eye position detection

Detection of changes in eye position in daylight using the brightness algorithm and simulated REM images had an accuracy of 70%. This result suggests that the brightness algorithm is a viable solution to eye position detection. The algorithm does not consist of any complex processes, making potential upgrades straightforward. One such upgrade would be to address the sensitivity to light. Small changes in lighting have significant effects on the resulting images and associated calculated brightness. Managing this brightness sensitivity through taking better pictures (camera and lighting) or adjusting the algorithm is possible.

Another consideration is the target accuracy. While 70% accuracy was achieved, 100% may not be necessary. Position data from images 3, 4, 5, and 6 in Figure 4 are close enough to the Left/Right line that small changes to brightness could change the position identification. The first REM cycle typically lasts about 10 minutes and the last cycle can last up to about an hour, with each cycle increasing in length throughout the night (Felson, 2020). With an average of 16 oscillations per minute lasting anywhere from 10-60 minutes, each REM cycle will produce about 160-960 eye position changes. Since the primary goal is to detect the onset and completion of a REM stage, a detection rate of less than 100% can still meet the detection requirement.

4.2 Hardware Discussion: Camera and Lighting

The Raspberry Pi camera was able to take pictures both in the dark with infrared lighting and in the light with bright lighting.

In the current prototype, the camera is able to be focused at a consistent distance from the eye. However, the focus of the camera depended on the distance of the camera from the eye as well as the lighting. Additionally, the large size of the Raspberry Pi camera made it difficult for the device to be able to fit comfortably on the user's head, preventing the person from being able to comfortably wear the device while sleeping. It is recommended to use another smaller computer like the Raspberry Pi Zero, which is a smaller version of the Raspberry Pi used. Using a smaller Raspberry Pi would also contribute to creating a smaller, more compact mask device so as to ensure the user's comfort.

Additionally, the results from pictures taken in the daylight resulted in some difficulty distinguishing eye position because of even lighting distribution throughout the image. Because the algorithm utilizes image brightness, focused light at a certain angle may give better results. IR light distributed throughout the image would most likely give very similar results to the current results. Additionally, we found the images with IR lighting had a shadow in the middle, consistent with an IR filter on the camera lens. It is recommended that a camera with no IR filter is used to capture better pictures that can work with the brightness algorithm.

4.3 Future Work

Complete software for this project requires additional development to fully assess the quality of sleep from a night. To measure the quality of sleep, frequency of eye oscillation, the length of each REM cycle, and the total number of REM cycles in a night must be calculated based on the eye position measurements. The process on how to collect this information has been developed and is shown in Figure 5. In addition to the calculations needed for sleep quality analysis, the collected data should be used to make recommendations that will influence behavioral choices and improve the quality of sleep.

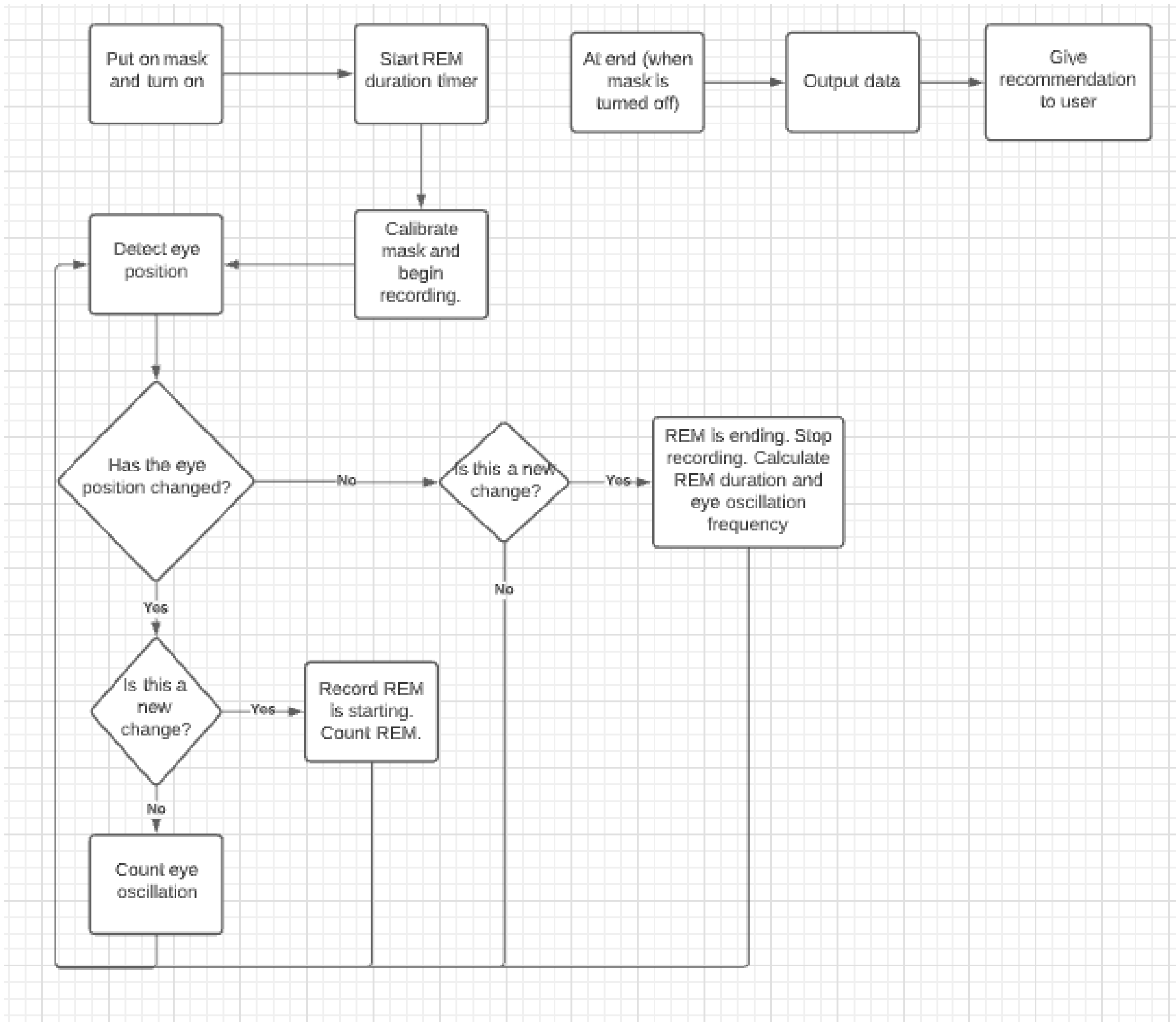

Figure 5: Device Flowchart

5.0 Conclusion

The insufficient amount of REM sleep for teens can lead to both short term and long term health problems. Information about REM sleep and its effects are not widely known among teens, so a way to easily and accurately track REM sleep was developed in an effort to improve the quality of sleep in teenagers. This project aims to not only track REM sleep but also report information that can lead to improved decisions about sleep routines and habits. Using a low cost camera, changes in position of a closed eye were detected with daylight illumination. These changes can be used to indicate the onset and occurrence of REM sleep throughout the night. A prototype of a mask device was built to demonstrate image acquisition in the dark with IR illumination and a project flow chart was developed to provide a path to completion.

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7.0 Appendices

Raspberry Pi camera setup:

https://projects.raspberrypi.org/en/projects/getting-started-with-picamera

Scikit-image code:

Template Matching:

https://scikit-image.org/docs/dev/auto_examples/features_detection/plot_template.html

Image Registration:

https://scikit-image.org/docs/dev/auto_examples/registration/plot_register_translation.html

Crop image code:

https://drive.google.com/file/d/1r_vfZ7tYrhtKehl3s6Yu9GRhdkDunEwx/view?usp=sharing

Centroid code:

Source:

https://stackoverflow.com/questions/48888239/finding-the-center-of-mass-in-an-image/48917207

IDLE:

https://drive.google.com/file/d/1PiEfKFTubRO9obUlv7v6pzagpHiujI3w/view?usp=sharing

Brightness algorithm code:

https://drive.google.com/file/d/1hP6SAzGdLco790kY-u--jybrlqKJmcSa/view?usp=sharing