Automatic detection of the REM sleep phase during electrooculography

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Abstract: *Sleep is not just a rest; it is a necessary part of the functioning of the cognitive system of people. Studying the role of sleep for effective functioning of the immune system, temperature regulation, memory, emotional regulation, learning and many other physiological and psychological processes is gaining more and more relevance. It attracts the attention of many leading researchers from around the world. The study of sleep by electrooculography (using three electrodes – two on the temples and one on the forehead) to track eye movements has a significant advantage over the more commonly used EEG methods due to its lower cost and the ability to quickly and efficiently collect large databases. A software-implemented algorithm for automatic recognition of the REM sleep phase during sleep is presented. This algorithm is a step of a larger project to create a system for external control of the content of dreams during REM sleep by providing scents and sounds, pre-associated with various stimuli and symbols. This system will allow in the future applying an automatic external influence on the sleeper during the REM phase. The development will have applications at research on the induction of selected elements during dreaming. This can help to people with post-traumatic stress disorder and phobias, as well for a more effective learning.*

Keywords*:* REM SLEEP, AUTOMATIC DETECTION, SLEEP SIMULATION, TARGETED MEMORY ACTIVATION

1. Introduction

Sleep is a crucial mechanism for numerous physiological and psychological functions [1, 2]. Various disorders and deviations from normal sleep patterns can severely affect the immune system, emotional regulation, memory, learning abilities, and other vital functions.

It was first discovered by [3] that sleep is not simply a monotonous state of unconscious rest, but instead, it has a complex structure. Sleep consists of a periodic rotation of stages that differ significantly from each other in terms of brain activity patterns and muscular activities (refer to Fig. 1).

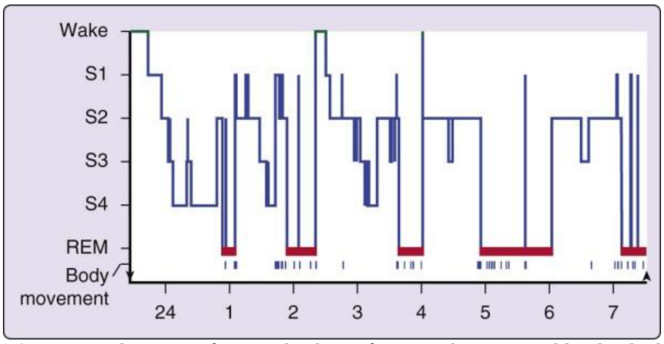

Fig. 1 *Typical pattern of one night sleep of a normal 19-years old individual (adapted from [4])*

Normal sleep can be broadly classified into two stages: *deep slee*p (NREM), which consists of various sub-stages, and paradoxical or *rapid-eye-movement* (REM) sleep. Empirical data, as reviewed in [1], indicate that during NREM, information from the hippocampus is transmitted to the cortex, leading to the deep encoding of important learnings from the day into long-term memory. This process prepares the hippocampus for further learning, while also erasing redundant information and regulating the sympathetic nervous system. As a result, traumatic information may also be deleted during this stage. Long-term deprivation of NREM sleep can lead to subjects remaining permanently in a "fight or flight" state, which may cause severe psychotic disorders.

The NREM stage of sleep is vital for any type of learning, including the acquisition of new motor skills. For instance, a study by [5] demonstrated that even a short nap can result in smoother and more accurate learned movements.

On the other hand, REM sleep is associated with creativity, remote analogies, and emotional regulation. During this phase, desynchronized electroencephalographic patterns are observed, which are indistinguishable from those of awake periods. The noradrenaline emotion is blocked, allowing recall of traumatic emotional memories without experiencing the associated emotions. All motor activities are also blocked, with the exception of quick eye movements, which give this stage its name - Rapid Eye-Movements.

One of the most significant empirical findings associated with REM sleep is that dreams occur more frequently during this stage. It is as if the brain prevents the body from possible injuries by blocking the muscles and noradrenaline emotion, leading to a paradoxical psychotic-like stage of dreams. Symptoms like hallucinations, delusions, confused and disturbed thoughts, and disturbed recognition of time, typical of severe psychotic patients, are normal for every healthy individual during paradoxical REM sleep. Adequate and quality REM sleep is essential for healthy emotional activities and is crucial for creativity.

It is not surprising that sleep studies have increased tremendously recently, thanks to the development of better monitoring techniques, and numerous brilliant researchers from all over the world are now focusing on this type of research..

2. Studying the sleep and its stages

Traditionally, electroencephalography ([6], [7]) has been the primary method for detecting the different phases of sleep. However, there are many other methodologies for studying sleep, which vary greatly according to criteria such as objectivity vs. subjectivity, contact vs. contactless devices, and more (see [8] for a review). Additionally, several methods are usually used simultaneously to obtain more reliable results and overcome the limitations of each separate method. The combined use of many different methods for studying sleep is known as polysomnography. Polysomnography may include two or more of the recording devices listed below (taken from [8], p.2):

Electroencephalogram (EEG) — measures and records the brainwave activity to identify sleep stages and detect seizure activity.

Electrooculogram (EOG) — records eye movements. These movements are important for identifying the different sleep stages, especially the REM stage.

Electromyogram (EMG) — records muscle activity (e.g., teeth grinding and face twitches; but also, limb movements using surface EMG monitoring of limb muscles, periodic or other). Chin EMG is necessary to differentiate REM from wakefulness, limb EMG can identify periodic limb movements during sleep (PLMS).

Electrocardiogram (EKG) — records the heart rate and rhythm.

Pulse oximetry — monitors the oxygen saturation (SO2).

Respiratory monitor — measures the respiratory effort (thoracic and abdominal). It can be of several types, including impedance, inductance, strain gauges, etc.

Capnography — measures and graphically displays the inhaled and exhaled CO2 concentrations at the airway opening.

Transcutaneous monitors — measure the diffusion of O2 and CO2 through the skin.

Microphone — continuously records the snoring volume and kind.

Video camera — continuously records video. It is useful to identify the body motion and position.

Thermometer — records the core body temperature and its changes.

Light intensity tolerance test — determines the influence of light intensity on sleep.

Nocturnal penile tumescence test — is used to identify physiological erectile dysfunctions.

Esophageal tests — includes pressure manometry, to measure pleural pressure; esophageal manometry to assess peristalsis, and esophageal pH monitoring (acidity test).

Nasal and oral airflow sensor — records the airflow and the breathing rate.

Gastroesophageal monitor — is used to detect Gastroesophageal Reflux Disease (GERD).

Blood pressure monitor — measures the blood pressure and its changes.

The list above includes both contact devices (such as EEG, EMG, EKG, etc.) and contactless ones (such as microphone, video camera, etc.). Each of these devices has its own advantages and disadvantages, and they vary in terms of their sensitivity and specificity in detecting different parameters of sleep. The parameters of sleep, in turn, can be numerous, but they are usually measured in terms of various time intervals. For example, the time when the participant goes to bed and when they leave the bed; the time when the first sleep stage begins and when the last sleep stage finishes; the amount of time spent in REM or NREM sleep, and more.

Sleep studies also include subjective methods such as questionnaires and sleep diaries. These methods can measure elements of sleep that objective methods cannot, such as the content of dreams or the precise emotional mood produced by sleep and/or dreams. Introspective methods may also include voluntarily depriving oneself of sleep for a short period of time or living in complete darkness for a couple of days.

In addition, studying animal sleep may provide us with data extracted using more invasive methods (see, for example, [9]).

Certainly, the combined use of several methods has its advantages, including the ability to measure many parameters and increased reliability. However, there are also some disadvantages to consider. One of these is the cost, as some devices, such as EEG, can be quite expensive and require consumables. Another disadvantage is the potential for information overload due to the large amount of data collected. This can increase the degrees of freedom, making it difficult to focus on the most relevant information and leading to false alarms and spurious relationships.

Electrooculography (EOG)

By attaching skin electrodes outside the eye, near the lateral and medial canthus, it is possible to detect a participant's horizontal eye movements. EOG is actually a type of Electromyography (EMG), which measures the electrical potentials that cause muscle contractions responsible for horizontal eye movements.

Construction of an EOG device is cheaper than that of more complex EEG machines, as it only requires three or even two electrodes and hardware for filtering out various types of noise. The signal from the EOG device is usually discretized for additional software processing. See Figure 2 for a diagram of a typical example of EOG output.

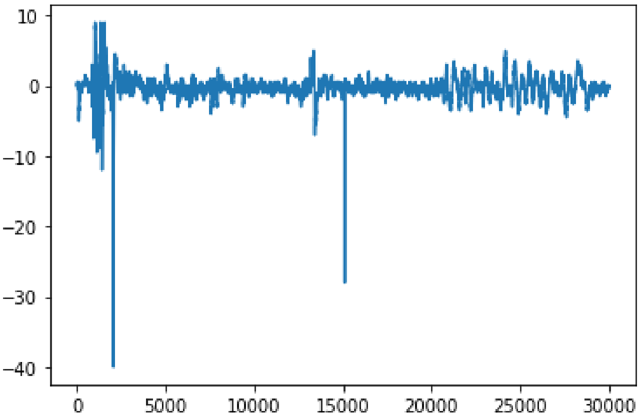

Fig. 2 *Example of a 5-minutes record of a dream by EOG. Time is on the horizontal line; the difference of the potential between the two electrodes is on the vertical line.*

The typical electrooculography presents the difference in potentials between the two electrodes as a function of time. The interpretation of this difference is a rapid eye movement, either to the left (positive numbers on the vertical axis) or to the right (negative numbers). It is important to note that if the participant moves their eyes to the left and then stops them (maintaining a constant gaze to the left), then the EOG signal will produce a large positive number, which will slowly decrease to zero. Thus, the device measures the initial change in eye position and returns to zero if the eyes remain motionless.

The output of the EOG device is a stream of numbers, which is a discretized version of the potential difference. This output can be visualized through a graph and can be designed with an arbitrary frequency. The work presented in this paper is based on an EOG signal that provides 100 numbers per second.

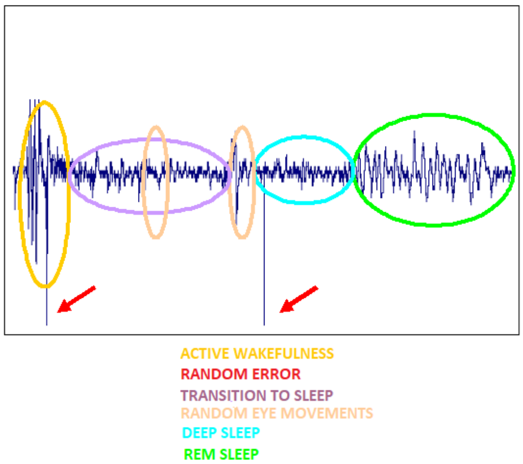

Fig. 3 *The different stages of the sleep could be easily recognized visually by looking on the graph but it is a challenge to design an automatic system for their on-line recognition.*

Electrooculography has a big advantage over the more frequently used EEG due to its lower cost. However, it is difficult to distinguish the EOG signal during different stages of NREM sleep, but it is reliable enough to detect the REM phase. Several algorithms have been developed for automatic detection of REM sleep using EOG ([10], [11], [12]). The challenge is that while it is relatively easy to visually detect REM by examining the EOG graph (see Fig. 3), automatic detection is difficult.

3. Algorithm for automatic detection of REM phase

We have developed a Python-based algorithm for automatic online detection of the REM phase of sleep using a continuously incoming stream of numbers. During program execution, the original signal (as shown in Figures 2 and 3) is transformed into an output consisting of a set of time intervals for each sleep stage (as illustrated in Figure 4).

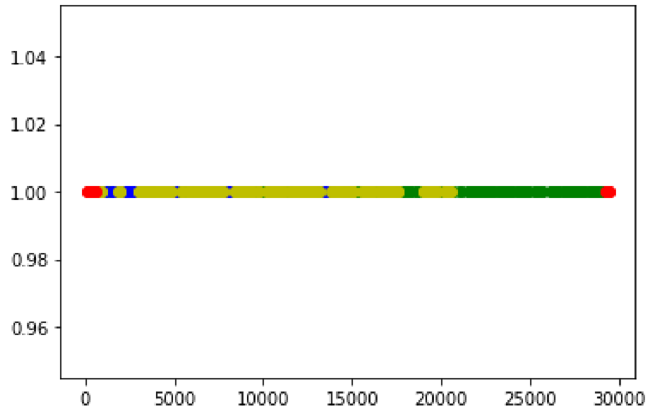

Fig. 4 *The output of the algorithm. In green is the most important part of the sleep – REM; in yellow is deep sleep; in blue – awakens; in red – undefined time intervals.*

The program relies on two primary parameters, along with some participant-specific ones. The first parameter controls the degree of smoothing applied to the data to eliminate random large fluctuations, while the second parameter controls the width of the time window used to detect the sleep stage. Increasing the smoothness parameter results in more data being removed, increasing specificity but decreasing sensitivity. Conversely, increasing the window width parameter results in higher accuracy but also higher time delay.

The algorithm consists of four main procedures: (1) smoothing the input data, (2) calculating estimates for the first derivative, (3) extracting main single eye movements (EM) and their amplitude, duration, and slope, and (4) generating the output of the program in the form of time intervals for each stage of sleep.

During the first procedure, the program sequentially analyzes the input stream. After reading one number, it returns the median of the set of previously read numbers, depending on the window width parameter. For example, if the window width is set to 5, then at each step, the algorithm returns the median of the last 5 numbers. The final result is a smoothed version of the incoming signal with high peaks removed (see Fig. 5).

The output signal of the first procedure replicates the main form of the original signal but without very high peaks, random errors, or detection of random single eye movements. The output signal has slightly smaller amplitudes of the waveforms than the original signal, but this difference is relatively small (see Fig. 5). The frequent small oscillations are also removed. In summary, after the first procedure, one can clearly see the main waves caused by the eye movements in the output signal.

During the second main procedure, a variant of the first derivative of these waves is calculated.

In the second main procedure, a window of numbers is again created around the focused number. For each element in this window, its difference from the mean of all numbers in the window is calculated, and this difference is then divided by the length of the time interval between the respective element and the middle of the window. This calculation follows the definition of the first derivative. Finally, the mean of all these ratios is obtained.

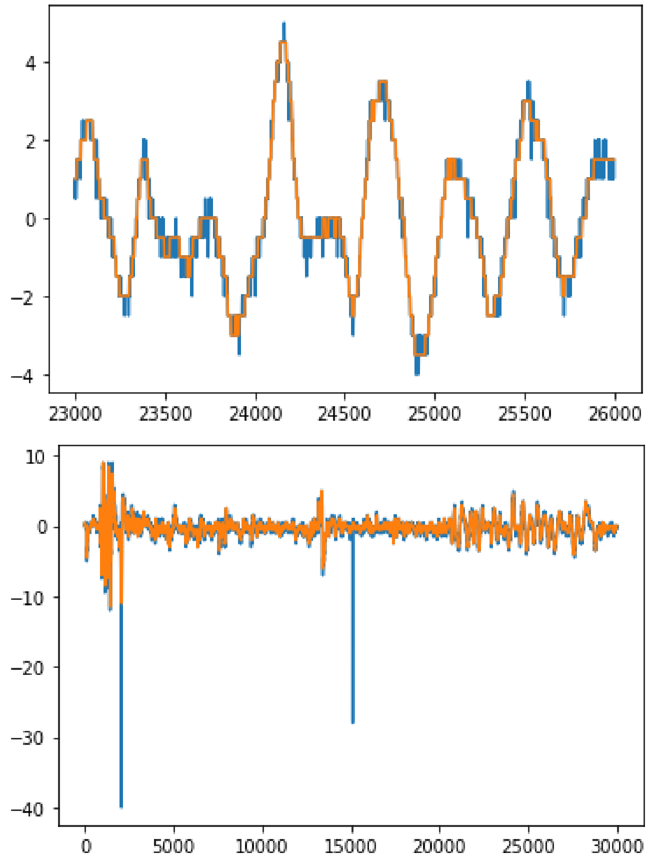

Fig. 5 *The original signal (in blue) together with its smoothed version (in orange). On the bottom panel is a small part of the data on the upper panel.*

The purpose of this whole procedure is to determine the sign of the derivative, i.e., the slope of the original curve. The output of the procedure is then used as an input for the next procedure, which extracts the separate eye movements (EM). This transformation effectively converts the signal into a set of distinct linear segments (as shown in Fig. 6).

The fourth procedure of the program is responsible for classifying each separate eye movement (EM) into one of four categories: wakefulness, deep sleep, REM, or undefined phase. This classification is based on the slope, duration (abscissa), and amplitude (ordinate) of each line segment representing an EM. The program allows for a certain tolerance level, which depends on a parameter, to avoid quick flipping between sleep phases. In other words, multiple consecutive EMs from the same sleep phase must be detected before the program concludes that the respective phase is present.

4. Conclusion

The conventional polysomnography method, which involves EEG, is typically considered too costly for many sleep research studies. In such cases, using EOG can be advantageous for collecting larger amounts of data. Although EOG may not have the same level of sensitivity as EEG for distinguishing between subtle sub-phases of NREM sleep, it is reliable enough for detecting REM sleep.

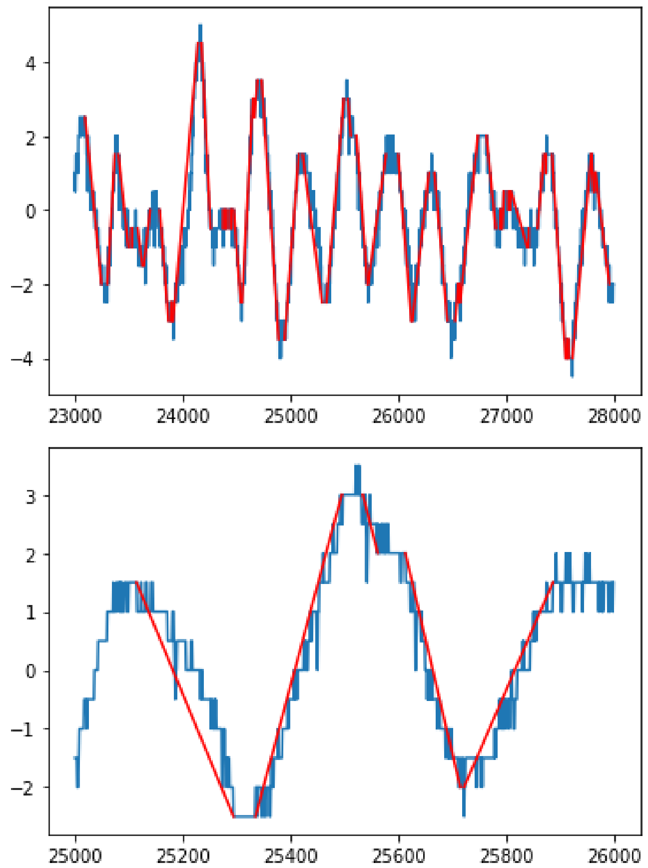

Fig. 6. *The data are transformed onto set of separate linear segments, representing the single EMs. The parameters of interest are the slope, the duration, and the amplitude of each segment. On the basis of these three parameters, the segment is classified as a part of a specific phase of the sleep. On the bottom panel is visualized a small part of the data on the upper panel.*

The visual detection of the REM phase of sleep by analyzing the EOG signal graph is relatively easy. However, the available algorithms for automatic detection are limited in their capabilities. To address this, we have developed a Python-based program that allows for the automatic on-line detection of the REM phase during data collection. This program has the potential to enable investigations into sleep using larger data sets and also facilitate active manipulation of sleep during the REM phase.

The presented results represent only the first step of a larger project, and there are still many shortcomings that need to be addressed. It is necessary to collect more data and precisely calibrate the parameters, taking into account the specific characteristics of each participant. To achieve this, a larger collection of sleep records should be obtained from different individuals sleeping in different contexts. Therefore, the results presented here can only be interpreted as preliminary steps towards the development of software for sleep analysis, and further calibration of the parameters is required.

Despite these limitations, the proposed algorithm could serve as a useful starting point for the development of future applications in this area.

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5. References

1. Walker, M. *Why we sleep: Unlocking the power of sleep and dreams*. Simon and Schuster (2017)
2. Moorcroft, W. H., & Belcher, P. Understanding sleep and dreaming (pp. 168-169). New York, NY, USA:: Kluwer Academic/Plenum Publishers (2003)
3. Aserinsky, E., & Kleitman, N. Regularly occurring periods of eye motility, and concomitant phenomena, during sleep. *Science*, 118(3062), 273-274 (1953)
4. Carskadon, M.A., & Dement, W.C. Monitoring and staging human sleep. In M.H. Kryger, T. Roth, & W.C. Dement (Eds.), *Principles and practice of sleep medicine*, 5th edition, (pp 16-26). St. Louis: Elsevier Saunders (2011)
5. Nishida M, Walker MP (2007) Daytime Naps, Motor Memory Consolidation and Regionally Specific Sleep Spindles. *PLoS ONE* 2(4): e341. https://doi.org/10.1371/journal.pone.0000341 (2007)
6. Armitage, R. The distribution of EEG frequencies in REM and NREM sleep stages in healthy young adults. *Sleep*, 18(5), 334-341 (1995).
7. Smith, J. R., Karacan, I., & Yang, M. (1978). Automated analysis of the human sleep EEG. *Waking & Sleeping* (1978).
8. Ibáñez, V., Silva, J., & Cauli, O. A survey on sleep assessment methods. *PeerJ*, 6, e4849 (2018).
9. Tran, S., & Prober, D. A. Methods to Study Sleep in Zebrafish. In *Circadian Clocks* (pp. 259-286). New York, NY: Springer US (2022).
10. Takahashi, K., & Atsumi, Y. Precise measurement of individual rapid eye movements in REM sleep of humans. *Sleep*, 20(9), 743-752 (1997)
11. Simor, P., van der Wijk, G., Nobili, L., & Peigneux, P. The microstructure of REM sleep: why phasic and tonic?. *Sleep medicine reviews*, 52, 101305 (2020)
12. Yetton, B. D., Niknazar, M., Duggan, K. A., McDevitt, E. A., Whitehurst, L. N., Sattari, N., & Mednick, S. C. Automatic detection of rapid eye movements (REMs): A machine learning approach. *Journal of neuroscience methods*, 259, 72-82 (2016)