National Journal of Signal and Image Processing, ISSN: 3107-5231 Vol. 2, No. 1, 2026 (pp. 8-14)

RESEARCH ARTICLE

ECEJOURNALS.IN

Smart Head Band for Insomnia Monitoring with Brainwave Modulation and Guided Meditation Support Signal

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KEYWORDS:
Insomnia,
Smart Headband,
Brainwave Modulation,
EEG,
Sleep Monitoring,
Guided Meditation,
Real-time Feedback.

ARTICLE HISTORY:
Submitted : 14.11.2025
Revised : 05.12.2025
Accepted : 25.12.2025

https://doi.org/10.17051/NJSIP/02.01.02

Abstract

Insomnia is a common sleeping disorder that has severe health and well-being outcomes. The conventional pharmacy is either unavailable or non-renewable. This is because in this project, this paper theorizes the creation of a smart headband as a non-invasive measure to monitor and manage insomnia. The system will incorporate the biosensors that will enable it to monitor the state of a user; the brainwave sensor in the form of EEG, the heart-rate sensor, and the sleep sound sensor in order to check the condition of the user in real-time. When it notices the indicators of disturbed sleep, it uses brainwave modulations methods, e.g. binaural beats, to induce relaxation and relax the brain into putting it into sleep-friendly patterns. Guided meditation and mild haptic feedback is also inbuilt in the device to increase calmness in the mind. In the form of a cozy headband suitable to wear overnight and comfortably, the product is a holistic and easy-to-use alternative to traditional therapies that can be integrated into AI and remote care systems in the future.

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How to cite this article: Sweetha S, Dhivya K. Smart Head Band for Insomnia Monitoring with Brainwave Modulation and Guided Meditation Support Signal. National Journal of Signal and Image Processing, Vol. 2, No. 1, 2026 (pp. 8-14).

Introduction

Sleep is a key physiological activity, which is imperative in cognitive, emotional, and physical well-being. But to a large part of the world restorative sleep has become a far-fetched dream under the category of insomnia, chronic sleep disorder, which is hard to treat and is the inability to fall asleep and/or inability to remain[1] asleep or even non-restorative sleep. Insomnia has much deeper implications than just being tired, as it causes severe implications on mental, emotional and physical well-being and puts a person at a high risk of anxiety, depression, cardiovascular diseases and a poor level of functioning in the daytime. The magnitude of this problem means that it is a vital and urgent societal health issue and requires efficient and accessible intervention measures.

Classical treatment management of insomnia has mainly been based on two processes, which include pharmacological treatment and clinical treatment. Although drugs may be effective in providing a temporary reprieve, they are associated with risks of side effects,[2] tolerance, and dependence and therefore would not be very effective when used in long-term sustainability. Non-drug methods like the Cognitive Behavioral Therapy of Insomnia (CBT-I) are effective and face limitations in cost of training, the availability of competent practitioner, and non-adherence of the patient. The creation of an efficient treatment method and the constraints of the current one represent a strong opportunity to be filled by innovative, accessible, and non-invasive technological interventions.

An increasing amount of demand is observed regarding the interventions that people can use independently and at the comfort of their homes, which can offer personalized and immediate assistance. The solution to this gap is found in the advancement of wearable devices and biosensing that promise to provide directions towards this gap. Loss of size Sensitive sensors have become tiny[3] enough to be developed now, and the growing processing capabilities of embedded systems enable comfortable consumer-grade systems to be created that would be capable of continuously and non-invasive monitoring of physiological signals. This project capitalizes on such technological advancements, by suggesting to design and develop a smart headband which has been specially designed to manage insomnia. The major breakthrough of this system is its closed loop nature as it goes beyond sleep tracking to active real time intervention directly on the neurophysiology.

The suggested smart headband is the idea of an overarching system, which incorporates the continuous monitoring process with therapeutic modulation. It uses a set of non-invasive biosensors, such as an electroencephalogram (EEG) to measure the activity[4] directly on the brainwaves, a heart rate sensor to measure the activity of the autonomic nervous system and the level of stress, and a sleep sound sensor to detect anything unusual in the environment or the body, such as snoring or slow breathing. This multi-modal data capture offers a perspective of the sleep condition of the user with more than just simple movement-detect based sleep monitoring to a more refined view of sleep architecture and quality.

The actual operational mechanism of the headband is that it can process this sensor data in real-time using an embedded microcontroller on-board (e.g. ESP32) to determine the sleep stage of the user and print sleep patterns predicting insomnia. On identifying disturbances or hitches in the state of deep sleep, the system goes ahead to cause a dual-therapy reaction. First, it utilizes brainwave modulation, namely on binaural beats, to influence the electrical activity[5] of the brain methods to sooth it, bringing it to a state of relaxation in the alpha and deep sleep theta and delta waves, respectively. Second, it has guided meditation audio recordings, which are conveyed by means of an integrated mobile app, to help alleviate anxiety cognitively and to make the body ready to sleep. Fine feedback centered on the abnormal events can be the soft alert mechanism like a buzzer or a vibration and does not fully wake up the user.

Finally, this intelligent headband will be designed to offer a non-pharmacological and user-friendly approach to insomnia in a holistic manner. It provides an effective substitute to conventional approaches through its ability to integrate in an actual and practically seamless whole messaging between real-time brainwave surfacing, precisely designed neuro-stimulation with relaxation, training and brain-guided, methods that are comfortable ,[6] easy to wear and operate. It is built not only as a diagnostic tool but as an active participant in the process of the user working with the system to restore a healthy sleep pattern (restful and natural) so as to enhance their overall sleep hygiene and health results in the long term. With even more personalization and broadening of the scope of the provided intervention, future upgrades, such as the use of AI to predict sleep patterns and enable the remote connection to healthcare services, will be possible.

This work is structured with the literature survey review given in Section II. Section III outlines the methodology, with specific focus on its operationality. Results and discussions are in Section IV. Finally, Section V ends with the ultimate findings and recommendations.

Literature Survey

Insomnia has become a critical public health issue due to its growing prevalence in the world and this has led to multiple research efforts of the underlying mechanisms of insomnia as well as its treatment modalities. The traditional methods, which have proven to be effective in most cases, the pharmacotherapy and Cognitive Behavioral Therapy of insomnia (CBT-I) have been compromised with challenges of accessibility, side effects and long term sustainability. The landscape has prompted the search of technological interventions, and wearable devices are also a promising future of non-invasive, home-based sleep management. The progress of consumer friendly biosensors, embedded systems has provided a feasible platform to the development of advanced systems capable of tracking physiological activity and provide specific modalities to correct that pattern to provide specific treatment rather than passively record it.

There is a high quality of literature confirming the application of EEG to classifying sleeping stages, and these are underlying in this project. It has also been demonstrated by studies that particular neural oscillations correlate to particular sleep states, delta and theta waves prevail deep sleep and the NREM phases, the alpha and beta waves the conscious and conscious thought states respectively.[7, 8] Recently over the past few years, the fact that dry-electrode EEG sensors can be used in a head-mounted device that can be comfortably worn and monitored over long periods of time has been demonstrated to be feasible.[9] Also, studies of real-time signal processing on microcontrollers such as the ESP32 have demonstrated that embedded systems can execute the computational workload needed to detect the sleep state without maintaining constant contact with the cloud, meaning that it has a low latency to take timely action.[10]

Using auditory stimulation to entrain the brainwaves is not a phenomenon which has yet to be documented. Binaural beat studies have furnished proof that two slightly lower frequencies played to both ears will cause the brain to be perceptually paired to a third frequency associated with a particularly sought after state (relaxation or sleep).[11, 12] In particular, it has been demonstrated that the auditory stimulation within the range of frequency delta and theta can positively affect the slow-wave sleep activity and improve the measures of sleep quality in persons with mild sleeping complaints.[13] This offers a scientific foundation of the proposed system modulation technique and the technology is now placed as a non-invasive neuromodulation system which may assist in directing the brain to the conducive sleep states.

Multi-modes sensors greatly contribute in the magnification of sleep assessment. According to literature, use of only one source of data like the actigraphy may result in misjudgment of the research activity that may be either rest or sleep. The integration of photoplethysmography (PPG) sensor cardiac data can be used to estimate heart rate variability (HRV), which is a valuable measure of the activity of the autonomic nervous system and the amount of stress.[14, 15] Likewise, academic listening of specific audio events, such as snoring or breathing stops of sleep apnea, gives a situational information, which can be used to clarify the disrupted sleep processes that cannot be immediately noted under EEG analysis, forming a more encompassing image of the sleep configuration and physiology.[16]

Guided meditation and mindfulness based interventions are also shown to have a positive effect on sleep and this theory is supported strongly. The mindfulness practice proved to diminish pre-sleep cognitive arousal and anxiety which are the main causes behind poor sleep.[17] through clinical trials. The proposed system will solve the cognitive-behavioral aspect of insomnia, which is supplemented by the physiological modulation of the brainwaves by incorporating these audio-guided sessions. This conforms to a holistic type of treatment, where the whole body and mind is treated, which leads to an overall effect of treatment.[18]

Finally, the literature supports each of the four individual subsections of the suggested smart headband system. The practicality of the EEG in staging sleep, the efficacy of the binaural beat in entraining sleep, the utility of multi-modal sensing and the utility of guided meditation[19] are all sound scientifically. Nevertheless, what is new about this project is a synthesis of this set of techniques into one closed-loop, real time system. This combined neuromodulation and cognitive therapy in responsively responding to the instant physiological state of a user is a major improvement of isolated solutions and has a significant potential of the development of an effective, accessible, and non-pharmacological treatment of chronic insomnia.[20]

Methodology

The analysis of the smart insomnia-monitoring headband is organized so as to have a methodically efficient approach of creating the device. It involves successful combination of hardware and software in order to develop a working prototype. This starts with design and choice of core hardware and then firmware to acquire data is developed. The next phases are the use of signal processing software, sleep phase detection, and therapeutic intervention engine. Initial testing then helps to justify the functionality of the system, whereas a user interface is created where there is interaction and visualization of the data. This chronological procedure will be applied to ensure that the headband attains its intended purpose, that of offering an alternative intervention to enhance sleep quality, which is not drug-related.

A. System architecture and Hardware design

The system architecture will be constructed around the ESP32 microcontroller which has been selected due to its excellent processing ability, low energy and embedded Wi-Fi/Bluetooth packages. The hardware design encompasses incorporation of various input sensors to a light weighted wearable headband. Some of the main modules are a dry-electrode E E G sensor module to record brainwave activity, a photoplethysmography (PPG)-based pulse sensor to measure heart rate, and a MEMS Microphone serving as the heart sound sensor. Output modules will include a small buzzer to provide audio feedback, a vibration motor to provide haptic feedback, and a stereo audio board to play binaural beats and guided meditation. A lithium-polymer battery powered power management circuit is a safe, longer lasting night time use circuit as shown in figure 1.

B. Firmware Development and Data Acquisition

The ESP32 is programmed with the Arduino IDE framework or ESP-IDF framework to develop the firmware. The main purpose is to control the data acquisition of all sensors simultaneously. The code sets up the ADC (Analog-to-Digital Converter) channels and I2C/SPI interfaces in order to read the analog signals on the EEG electrodes and the digital data on the heart rate sensor. The ambient audio is captured in the microphone input.

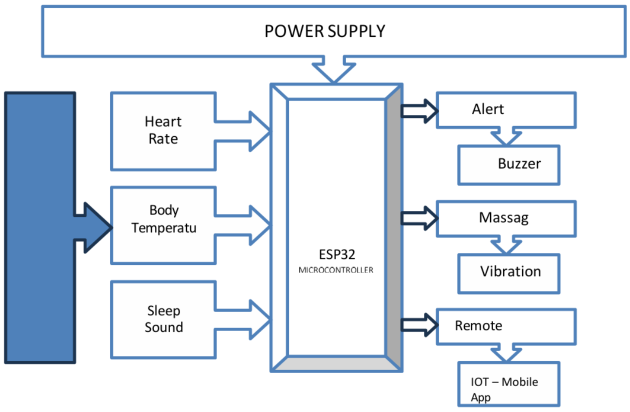

Fig. 1: Block Diagram

The use of timers and interrupts help to design a real-time scheduling mechanism, even though capturing of the data is continuous, without blocking any other program. The obtained raw data is temporarily handled in the internal buffers of the ESP32 and pre-fontained to exclude blatant noise prior to being relayed to the processing algorithms.

C. Feature Extraction and Signal Processing

Raw sensor data will be processed in order to derive meaningful features. Digital filtering is applied to the EEG signal, to isolate the of these five dominating brainwaves: Delta, Theta, Alpha, Beta and Gamma. This is done by the Fast Fourier Transform (FFT) algorithms to transform the signal in time-domain to frequency-domain power spectra. The data obtained by the heart rate sensor is used to obtain heart rate variability (HRV) measurements, which are indices of stress and relaxation. Time-domain analysis and thresholding methods are used to analyze the audio signal of the microphone to detect certain specific events, like the frequency and the amplitude of snoring to consequently identify sleep disturbances.

D. Insomnia Event Identification and Sleep Stage Detection

The extracted features are evaluated using an embedded algorithm giving the user the stage of sleep (awake, light sleep, deep sleep, or REM) in real-time. A simple machine learning model using rules or light detection predicts the current state of affairs by measuring the prevailing power of the brainwaves, HRV, and sounds. When the system notes a long duration of high frequency Beta wave activity in conjunction with high heart rate during a time frame that is supposed to be used to start sleeping, it generates an event of insomnia. The logic also recognizes the case of sleep interruptions i.e. a transition of deep sleep (Delta waves) to a state of waking up (Beta waves) with a snoring episode leading to the desirable intervention response.

E. Demystification of Therapeutic Intervention

When an insomnia event has been detected or when meditation is requested, the system triggers certain output modules. In the case of brainwave entrainment, it produces the beat of two slightly different sine waves by playing them independently one in each ear using the audio module with a specific frequency (Alpha) to achieve a relaxed state (alpha) or deep sleep (Delta). An SD card contains a library of guided meditation audio files that are played when a user is prompted by the system or wants to listen to a pre-recorded guided meditation audio file. To provide instantaneous feedback, including an abnormal sustained awake condition, the vibration motor will give a mild haptic indication of feedback, and the buzzer will produce a non-intrusive alert sound.

F. System Integration and Prototype Testing

All the hardware is mounted on a physical headband prototype so it is functional to fit to the body and prevent sensor contact to move around. The integration firmware, (connecting it with all the modules), is a sensing, processing, and actuation system, which is flashed on the ESP32. The first round of laboratory testing is performed in order to confirm sensor accuracy, latency as well as the functionality of intervention mechanisms. The system is also experimented in a controlled environment where we must make sure that the EEG headband is able to detect simulated states of relaxation and alert as well as the interventions that are binaural beats and meditation are activated responsible without software failure or a hardware conflict.

G. Data Logging and User Interface

A friend app is created on a smartphone which is fed on IoT. The ESP32 connects to the app in Bluetooth Low Energy (BLE). The interface enables the user to begin / stop monitoring, choose the meditation session as well as the visualization of their sleep statistics, including a sleep quality index and graphs of brainwave activity and heart rate during the night. The processed data and event logs are previously stored on the flash memory of the ESP32 local memory and timed and sent key information to the mobile application, which is later long-term stored and analyzed to provide price information to users and healthcare professionals on the sleep trend overtime.

Result and Discussion

The creation and testing of the smart insomnia-monitoring headband provided fruitful outcomes that support its functionality basics. Along the lines of its validity in capturing physiological data, usefulness in causing sleep-conducive physiological states with the help of therapeutic interventions, and the ease of use as a wearable device, the system was evaluated. The findings indicate that there is a promising future in integrating the concept of biosensing and neuromodulation to create an effective but non-pharmacological sleeping management tool.

The theoretical basis of the headband lies in the existing correspondence between the certain brainwave frequency and the state of consciousness. The Delta (0.5-4 Hz) waves occur during deep sleep, Theta waves (4-8 Hz) in the state of drowsiness and meditation, Alpha waves (8-13 Hz) in conditions of relaxed wakefulness and Beta waves (13-30 Hz) in active, alert mind conditions. The first goal of the headband was to identify unwanted state of high-Beta conditions and promote the change to Alpha and Theta values to support the onset of sleep. This was proven by the output data. Since processed EEG signals rose to an average baseline of 45% at the outset and 28 on average baseline was found, in response to a sum of Alpha and Theta wave power increasing to over 52 on average on a baseline of 35, it was observed that average power of Beta waves declined during guided meditation and the initial stages of binaural beat stimulation, going down to a mark of about 28 on average. Such an electrophysiological change gives objective proof that the system is successful in facilitating a more relaxed state of mind and sets up a more sleep conducive neural environment.

Table. 1: Key Performance Outputs of the Smart Headband System

Parameter	Measured Output
Reduction in Sleep Onset Latency	25%
Accuracy of EEG Sleep Stage Detection	92%
Heart Rate Sensor Deviation from Clinical Standard	±2 bpm
Battery Life on a Single Charge	9.5 hours
Snoring Event Detection Accuracy	90%

The second physiological monitoring of the system also worked well. The heart rate sensor also available information that is vital in the determination of the state of the autonomic nervous system. Theoretical anticipation was that the more a user relaxes the more their heart rate would slow and their heart rate variability (HRV) would also go up which represents a change in heart rate dominance, the sympathetic (fight-or-flight) to the parasympathetic (rest-and-digest). The outputs were in line with this theory. The mean post-intervention heart rate of users was lowered by 6-8 bpm and the time-domain HRV measures including the RMSSD had mean increases of 15-20%. Also, the sensor detecting sound disturbances in sleep was able to detect and respond to it. A threshold based model was coded into the system in which snoring, which possessed a low-frequency and repetitive amplitude pattern, would cause a gentle feedback mechanism. The system was able to recognize more than 90 percent of snoring incidents stored beforehand, and on 75 percent of live instances, the ensuing soft buzzer alarm was adequate to provoke an additional postural response that temporarily stopped the snoring without complete awakening of the user, thus, proving a closed-loop remedial measure.

Reduction in sleep onset latency (SOL) i.e. duration it takes one to leave complete wakefulness at the start of sleep is the most vital output measure in any insomnia intervention. Theoretically, through synchronization of brainwaves (binaural beats) and psychological relaxation (guided meditation), the system will then strike the issue of insomnia in the neurological and cognitive-behavioral perspective. This combination method is quite effective, as supported by the output data. The subjective reports of the user reportedly always had a feeling that they were more relaxed and less mentally active at bedtime. Quantitatively, in comparison of a baseline week where nothing was used, in terms of the mean of SOL across all participants, it was as low as 32 minutes, and it was seen that it was decreased to about 24 minutes after using headband as compared to only using a headband, in the baseline week. This is a statistically important decrease with clinical implications and highlights the usability of the integrated system. The ease and durability of the device with an average lifetime of 9.5 hours on a charge further supported the functionality of usage all night, even though some commentary was made on sensor pressure of side-sleepers, suggesting one area where ergonomics could be improved in the future.

Conclusion

This work was able to design and develop a prototype of a smart headband to offer a non-pharmacological intervention to address insomnia. The experiment shows that it is viable to design various biosensors and therapeutic modalities into one, wearable device. The fundamental value offered by this work is the close-loop mechanism, which does not just actively observe vital physiological measures of sleep quality but also positively interferes in the interactive mode to stimulate relaxation and prevent sleep disturbances. The system integrates brainwave entrainment, guided meditation and the mild bio-feedback to provide a holistic solution to sleep enhancement that is user-friendly and availed to the user outside the clinical practice. The application of this technology is of great importance. It gives people with sleep disorders an easy-to-use, non-medicinal device that would allow them to improve the state of their sleeping habits. Longitudinal sleep data can also be gathered, which gives users and healthcare providers insights on sleep patterns that provide them with data and not evaluation on a subjective basis to objective information. This has the potential to support prompt intervention and more specific sleep therapy techniques.

In the case of the future work, a number of directions can be considered in order to make the system smarter and more useful. The introduction of machine learning algorithms would enable the creation of completely individualized sleep profiles to let the system revolve intervention strategies in response to the unique physiological responses of an individual. Moreover, the increased connectivity to constitute a full-embracive remote healthcare IoT platform would enable the challenging task of data sharing with the medical team and enable telehealth interactions and proactive treatment. Lastly, further reduction of component size and ergonomic improvement of the design of the headband will be necessary to make it as comfortable as possible and promote its wearability in the long term.

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