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Enhanced Sleep Quality Through Light Modulation IoT-Based Approach ESP32 with Philips Hue Integration

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ABSTRACT

This research aims to revolutionize sleep enhancement by developing a customized Internet of Things (IoT)-based system utilizing the ESP32 microcontroller, Philips Hue Bridge, and Bulb technology. The primary objective is to identify optimal lighting conditions conducive to improved sleep, considering factors such as color intensity and aligning with users' circadian rhythms. The system dynamically controls light intensity and color based on personalized profiles, synchronized with distinct times of the day, enhancing sleep quality. The integration of user profiles based on age refined these light profiles, addressing diverse sleep needs across age groups. Real-world experiments successfully validated the system's effectiveness across various age categories, demonstrating its application for tailored sleep solutions. The study makes a significant contribution to IoT-driven sleep interventions, setting a new standard for personalized approaches in the industry. Based on the successful implementation of the testing phase, recommendations for further refinement and expansion of the system are provided, such as exploring additional environmental factors for enhanced personalization, refining algorithms for improved real-time adjustments and considering user feedback for continuous system optimization. The study presents a groundbreaking solution for sleep enhancement and provides a roadmap for future advancements in personalized IoT-based interventions.

Key words : Embedded System, ESP32 Microcontroller, Healthcare Innovation, Healthcare Technology, Internet of Things (IoT), Real-world Experiments, Sleep Monitoring, Snoring, Snoring Decibel, Snoring Frequency.

1. INTRODUCTION

The Internet of Things (IoT) significantly impacts the medical sector, particularly in advancing sleep technology by facilitating the monitoring and enhancement of sleep patterns [11]. IoT devices, such as smartwatches, rings, and headbands, gather and analyze data on sleep patterns, quality, and duration, sending this information to smartphones via Bluetooth [9]. These devices also manage sleep environment factors such as light, temperature, and air quality, optimizing conditions for improved sleep [9]. Additionally, IoT and embedded technologies like the ESP32 allow for integration with other devices, enhancing connectivity and functionality [5].

The human body's internal circadian rhythm, regulated by the suprachiasmatic nucleus (SCN), controls sleep and wakefulness patterns and melatonin production. Proper alignment of this rhythm supports healthy sleep, while disruptions can cause sleep issues like insomnia [12][16]. Exposure to blue light during the day is vital for maintaining these rhythms, influencing alertness and mood [2]. Light therapy, or phototherapy, employs devices that emit light similar to natural sunlight to treat conditions like insomnia, circadian rhythm disturbances, and other mood disorders [10]. The use of amber light in such therapies has been found to suppress melatonin, aiding in relaxation and sleep [14].

The IoT's role in the medical field is expanding, offering solutions to various global challenges through smart devices and technologies like the ESP32 microcontroller, which is known for its power efficiency and connectivity options [6][8]. Furthermore, integrating IoT solutions like the Hue Bridge and Hue Light Bulb can sync with circadian rhythms to naturally enhance sleep environments, demonstrating IoT's broad potential in improving health and well-being [1][7].

2. BACKGROUND

A study by [1] evaluated the ESP32 microcontroller for IoT, highlighting its cost-effectiveness and dual-core processor, and included a comparative analysis and a practical example involving a wireless oscilloscope [1]. Explored the critical role of bit rate performance in 5G communications, discussing influences like bandwidth and modulation on quality of service and challenges like signal interference [3]. Research by [5] on circadian rhythms and sleep disorders discussed the molecular mechanisms and impacts of circadian disruptions on health, emphasizing the need for lifestyle adjustments [5].

Conducted a meta-analysis on the effects of light exposure on sleep in polar regions, finding that intense summer light negatively impacts sleep, whereas moderate natural light offers benefits [6]. Examined the impact of extended light/dark cycles on Solanaceae plant growth, showing that certain cycles improve plant development and yield under controlled conditions [7]. Investigated the effects of lighting on piglet houses, suggesting optimal lighting intensities and durations for improving piglet wellbeing and immune responses [8].

Focused on web server log analysis, developing software to manage and analyze server data, reflecting on the dynamic nature of web technologies [9]. Studied the effects of LED white light treatment on 'Zaosu' pears, demonstrating its role in enhancing postharvest quality and delaying senescence [10]. Finally, explored amber light treatment on tree shrews, indicating that it leads to hyperopia by affecting the long-wavelength sensitive cones, contrasting effects between different exposure setups [11].

A study referenced as focused on the quantitative analysis of color combinations from LED and laser light sources, using the modified CIE 1931 color space (figure 1). The research involved analyzing the light spectra of three LEDs and three laser sources emitting colors across the spectrum from blue to purple. Utilizing a spectrophotometer and adapted color matching functions, the study quantified 26 LED color combinations and 7 laser-derived combinations. It highlighted the potential for further methodological improvements to enhance the reliability of the results [25]

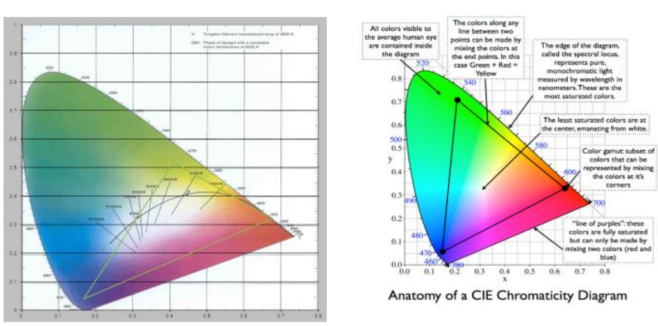

Figure 1: CIE 1931 Color Space and CIE Anatomy Chromaticity Diagram

The color of a Hue LED light is set by picking a position in the CIE 1931 color space, and there are several methods for doing this: setting an X/Y value within the allowed space (denoted by the green triangle in the picture above), or choosing a point along the black curved line specified in values of "reciprocal megakelvin," or calling out pure hue and saturation numbers.

2.1 Light Profile

Table 1: Light Profile

Light Type	Color Temperature (Kelvin)	Lumens(Approximate)
White Light	5000-6500	800-1600
Amber Light	2000-3000	300-600

2.2 Sleep by Age Profile

Table 2: Sleep by Age Profile

Age Range	Recommended Hours of Sleep Per Day	Ideal Bedtime
Newborn	14 to 17 hours	N/A
Infant (4-11 months)	12 to 15 hours	6 - 7 p.m.
Toddler (1-2 years)	11 to 14 hours	7 - 7:30 p.m.
Preschool (3-5 years)	10 to 13 hours	7 - 8 p.m.
School-age (6-13 years)	9 to 11 hours	8 - 9:30 p.m.
Teen (14-17 years)	8 to 10 hours	9 - 10:30 p.m.
Young adult (18-25 years)	7 to 9 hours	8 - 12 p.m.

According to [26], the amount of sleep needed can vary depending on individual factors such as family schedules and individual temperament (Table 2). However, the provided chart offers a general guideline for recommended sleep across different age groups. Light therapy, commonly known as light exposure therapy or phototherapy, utilizes a specialized device called a light therapy box, which emits bright light similar to natural sunlight. This method is employed to address various health conditions such as insomnia, circadian rhythm sleep disorders, seasonal affective disorder (SAD), depression, jet lag, night shift work, and conditions like Alzheimer's disease or dementia. The Pittsburgh Sleep Quality Index (PSQI), a widely acknowledged and valuable tool for evaluating sleep quality and identifying sleep-related disturbances, is frequently incorporated into research to explore sleep patterns and their implications for overall health and well-being [27].

3. OPERATIONAL FRAMEWORK

A strategic selection of key materials and components is imperative to successfully develop and implement an IoT-based approach for enhancing sleep quality through light modulation using the ESP32 with Philips Hue integration. These components can be broadly classified into hardware and software, forming the essential foundation for constructing a functional prototype capable of dynamically altering light functions to optimize sleep environments.

3.1 Materials

The study progressed through phases of design, implementation, testing, and evaluation. In the design phase, the researchers identified and acquired necessary hardware (e.g., ESP32, microphones) and software tools (e.g., Arduino IDE, Visual Studio Code) (Table 3). Prototyping involved connecting hardware components, illustrated in pin connection tables for ESP-A and ESP-B modules.

Table 3: List of Components

ESP32-WROOM-32 Micro controller Board	ESP32-WROOM-32 Micro controller Board	ESP32-WROOM-32 Micro controller Board	ESP32-WROOM-32 Micro controller Board
Philips Hue Bulb White and Color 1100	Philips Hue Bulb White and Color 1100	Philips Hue Bulb White and Color 1100	Philips Hue Bulb White and Color 1100
Philips Hue Bridge 2.1	Philips Hue Bridge 2.1	Philips Hue Bridge 2.1	Philips Hue Bridge 2.1
Wi-Fi Router (Huawei)	Wi-Fi Router (Huawei)	Wi-Fi Router (Huawei)	Wi-Fi Router (Huawei)
Laptop	Laptop	Laptop	Laptop

The researchers in this study focused on Algorithm Implementation and data collection, The experimental design implemented in this study aimed to assess the performance and functionality of the smart lighting control system, utilizing the ESP32 microcontroller in conjunction with the HUE Bridge and hue bulb within the broader scope of the Internet of Things (IoT) (Table 4).

Table 4: Summative Table of Experiments

ID	XP 1	XP2	XP3
AGE	29	42	22
AMBER LIGHT	x: 0.5600, y: 0.4200	x: 0.5600, y: 0.4200	x:0.5600, y: 0.4200
WHITE LIGHT	x: 0.3670, y:0.3707	x: 0.3670, y:0.3707	x: 0.3670, y:0.3707
PRE-SET SLEEP TIME	1:51 AM	9:56 PM	10:00 PM
PRE-SET WAKE UP TIME	7:10 AM	6:10 AM	6:40 AM
ACTUAL SLEEP TIME	1:29AM	11:19 PM	10:26 PM
ACTUAL WAKE UP TIME	7:49AM	06:01 AM	06:31 AM

4. SUMMARY, CONCLUSION, AND RECOMMENDATION

4.1 Summary

The study sought to create a sleep monitoring system by utilizing ESP32 for embedded system design, with a primary focus on capturing significant sleep data for expert medical analysis. The objectives encompassed the identification of essential components, the creation and refinement of a prototype, the implementation of an algorithm through Arduino IDE, and the subsequent testing to validate the system's overall performance [6].

During the requirements specification phase, the researchers collected crucial data, outlined data requirements, and examined relevant literature. The hardware selected, particularly the ESP32 and Philips Hue system, demonstrated multitasking ability and diverse features essential for lighting adjustments. Software choices, Arduino IDE and Visual Studio Code, were chosen to provide robust firmware management and advanced code-editing capabilities, establishing a solid foundation for system development.

The prototyping and development phase involved overcoming challenges in selecting appropriate modules and IoT devices. The researchers utilized Figma for conceptualizing the prototype and platforms like Arduino IDE and Visual Studio Code for programming and algorithm testing. Challenges in seamless integration of components were progressively addressed, refining the system.

In the Algorithm Implementation phase, the team encountered challenges in integrating specific API endpoints crucial for system functionality. Extensive documentation was reviewed to understand API functionalities, and troubleshooting was a recurring theme to ensure smooth communication between system components. The emphasis was not just on coding but on solving problems, implementing error handling, and ensuring real-time responsiveness for precise light control, aligning with the end goal of enhancing sleep quality.

In Test and Evaluation, despite encountering initial errors, the researchers adeptly addressed and resolved issues, resulting in the seamless functioning of the system. The process involved identifying and rectifying errors to ensure optimal performance, demonstrating the researcher’s capability to overcome challenges and achieve a flawlessly operating sleep monitoring system.

4.2 Conclusion

The smart lighting control system, driven by the ESP32 microcontroller, successfully accomplishes its primary objective of delivering seamless and personalized lighting adjustments for enhanced sleep experiences. The remarkable speed and reliability demonstrated by the HUE Bridge significantly contribute to the overall success of the system. Despite encountering challenges such as hardware initialization and signal reception, effective resolutions were implemented.

In conclusion, the study affirms the tremendous promise of the smart lighting system, with its sustained success dependent on continuous refinement and adaptation to ensure optimal performance in the ever-evolving landscape of sleep technology. The experiments conducted across different settings, including spatial constraints, hotel rooms, and residential bedrooms, collectively demonstrate the reliability and effectiveness of the system. Positive patient feedback and favorable PSQI scores validate the technology's positive impact on sleep experiences, and its resilience in mitigating potential sleep-disrupting factors underscores its practical functionality.

Furthermore, the calculated average PSQI score of 7.67 from experiment participants indicates a Good Sleep Quality, affirming the system's capability to contribute to an improved sleep experience. The system's robust and good performance, as observed throughout the study, reinforces its potential for widespread application in various environments. Overall, the findings support the notion that integrated smart lighting systems can significantly enhance sleep quality for users.

4.3 Recommendation

- Machine Learning Algorithms: Implementing machine learning algorithms could enable the system to adapt and learn from individual user preferences and responses over time. This would enhance the system's ability to dynamically adjust lighting conditions based on the user's evolving sleep patterns and preferences.
- User Behavior Analysis: Conducting a more in-depth analysis of user behavior and adherence to suggested sleep schedules could offer valuable insights. Integrating sensors or wearable devices to monitor sleep-related behaviors would provide a more holistic view of the user's sleep environment.
- Cross-Cultural Considerations: Expanding the study to include participants from diverse cultural backgrounds could provide insights into how cultural factors influence sleep patterns. Understanding these variations can contribute to the development of more universally effective sleep enhancement systems.
- Long-Term Impact Assessment: Conducting longitudinal studies to assess the long-term impact of the IoT-based sleep enhancement system on users' sleep quality and overall well-being would be valuable. This could involve tracking participants over an extended period to observe sustained benefits and any potential drawbacks.
- User Interface and Experience (UI/UX) Optimization: Improving the system's user interface and experience through iterative design processes can enhance user interaction. This includes developing user-friendly mobile applications.

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