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Influence of Environmental Factors on Sleep Quality: Analyzing Light Exposure and Sleep Duration with Smartwatch Data

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Abstract: Artificial lighting significantly influences circadian rhythms and sleep quality. This case study investigates the impact of environmental factors including temperature, relative humidity, CO_2 concentration, total volatile organic compounds (TVOC) and exposure to different light spectra on light sleep duration in a single subject. Sleep data were collected using a Xiaomi Mi Band 6 smart wristband, while environmental parameters were monitored with a custom Arduino-based sensor system. The results indicate that the optimal temperature for light sleep ranges between 17 and 21 °C, with the longest light sleep recorded at approximately 18 °C. Humidity, CO_2 and TVOC levels showed no significant effect on light sleep duration. Regarding light exposure, the longest light sleep occurred in complete darkness, while the shortest was observed under red light. However, the light spectrum did not show a consistent impact on light sleep duration, suggesting that its influence may be more pronounced in deeper sleep stages. Since this is a single-subject study, the findings are preliminary and not generalizable. Further research involving a larger sample size is needed to validate these observations and better understand individual differences in sleep responses to environmental conditions.

Keywords: light sleep; environmental factors; temperature; humidity; air quality; CO_2 levels; sleep tracking; Arduino

1. Introduction

Artificial lighting has become an integral part of modern life, significantly altering natural sleep patterns and circadian rhythms. Prolonged exposure to artificial light, particularly during evening and night-time hours, has been shown to disrupt sleep quality and interfere with the body's internal clock. While it is well established that light influences circadian rhythms, recent findings indicate considerable individual differences in how light affects physiological processes such as melatonin suppression. Despite growing evidence of these variations, recommendations for appropriate light exposure in real-world conditions often fail to account for individual sensitivity [1].

Throughout human evolution, the natural cycle of daylight and darkness has been the primary regulator of biological rhythms. However, artificial lighting has reshaped human activity, extending wakefulness beyond natural daylight hours. As a result, increased exposure to artificial light at inappropriate times or a reduced contrast between day and night lighting conditions has been linked to adverse health outcomes. Light exposure plays a crucial role in regulating the sleep-wake cycle, influencing body temperature, metabolism, and behavioural patterns such as eating and physical activity.

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In addition to light, environmental factors such as temperature, humidity, and CO_2 concentration can also influence sleep quality and may further affect the body's ability to synchronize with natural rhythms. Disruptions in these processes have been associated with metabolic disorders including obesity and diabetes. Studies suggest that multiple properties of light, such as intensity, duration, timing, and wavelength, contribute to these effects. Understanding the physiological impact of light and environmental conditions is essential for developing strategies to mitigate the potential health risks associated with modern lighting environments [2].

Insufficient sleep and disruptions in circadian rhythms are recognized as significant contributors to various health complications. Poor sleep quality has been associated with an increased risk of cardiovascular disease, hypertension, immune system dysfunction, and cognitive decline. Disturbances in the sleep-wake cycle have also been identified as key factors in the development of chronic sleep disorders. Light exposure plays a fundamental role in circadian rhythm regulation by influencing melatonin secretion and adjusting the biological clock through specialized photoreceptors in the hypothalamus. Maintaining a stable light-dark cycle along with optimal environmental conditions is essential for synchronizing physiological processes and supporting overall health [2].

1.1. Influence of Environmental Factors on Sleep

Sleep quality is influenced by various environmental factors, including temperature, humidity, air composition, and light exposure. Studies have shown that conditions such as excessive heat, high levels of carbon dioxide (CO_2), or volatile organic compounds (VOC) can disrupt sleep patterns and reduce overall sleep efficiency.

The optimal sleep temperature ranges between 17–21°C, as it supports thermoregulation and sleep continuity. The bedroom should be well-ventilated and cooler than other rooms to facilitate the natural decline in core body temperature necessary for sleep onset. Temperatures exceeding 24°C can disrupt sleep architecture, reducing sleep efficiency and increasing wakefulness [3].

Indoor air naturally contains water vapour, which directly influences humidity levels and impacts overall comfort and health. The ideal relative humidity falls within the range of 40-60%, as this helps maintain optimal respiratory function and prevents irritation of the skin and mucous membranes. When RH drops below 30%, humidification becomes necessary to mitigate discomfort and potential health effects, such as dry skin, throat irritation, and increased susceptibility to respiratory infections. Extremely dry air, with RH levels below 20%, can exacerbate eye irritation, dryness of the mucous membranes, and even contribute to respiratory discomfort by impairing the body's natural defence mechanisms against airborne pathogens [4-5].

CO_2 is the most prevalent indoor air contaminant, with concentrations consistently exceeding outdoor levels due to human respiration and inadequate ventilation. In enclosed spaces, pollutant levels can be two to five times higher than in outdoor air, particularly in poorly ventilated environments. Since CO_2 is colourless and odourless, humans cannot directly perceive its concentration, making subjective assessments of air quality unreliable [6-8].

CO_2 levels are measured in parts per million (ppm) and should not exceed 1000 ppm over an 8-hour period to maintain indoor air quality and occupant well-being (Table 1). Prolonged exposure to elevated concentrations can lead to a perception of stale air, morning fatigue, daytime sleepiness, headaches, and impaired cognitive function. Higher levels may also contribute to respiratory discomfort, particularly in vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions. Proper ventilation and air exchange are essential to mitigating these effects and ensuring a healthy indoor environment [9-12].

Baniassadi et al. (2023) emphasize that indoor air pollution remains a significant public health concern, often underestimated due to the predominant focus on outdoor air measurements, despite the fact that people spend most of their time indoors. The authors highlight that such exposure may contribute to millions of premature deaths annually. [13].

After CO_2 and CO, volatile organic compounds (VOC) are the third most commonly measured gases in indoor environments. Instead of measuring individual VOCs, their total concentration (TVOC) is typically assessed. VOCs are organic chemicals that become gases at room temperature, originating from everyday products and contributing to indoor air pollution. They may or may not have a noticeable odour. High VOC levels can be harmful,

Table 1: CO_2 concentration levels and air quality ratings [12].

CO_2 [ppm]	Air Quality
2100	BAD Heavily contaminated indoor air Ventilation required
2000	
1900	
1800	
1700	
1600	
1500	MEDIOCRE Contaminated indoor air Ventilation recommended
1400	
1300	
1200	
1100	
1000	FAIR
900	
800	GOOD
700	
600	EXCELLENT
500	
400	

causing eye, throat, and nose irritation, respiratory infections, allergies, headaches, and nausea. Based on TVOC concentration, air quality can be classified into different hygienic levels, ranging from excellent (<0.3 mg/m^3, 0–65 ppb) to unhealthy (10–25 mg/m^3, 2200–5500 ppb), where increased ventilation is recommended for higher levels (Table 2). TVOC represents the total concentration of VOCs in the air, measured in parts per billion (ppb) or milligrams per cubic meter (mg/m^3). However, there is no universally defined standard specifying which VOCs are included in TVOC measurements [14-15].

1.2. Research Aim and Summary of Results

This study aims to investigate the impact of selected environmental factors, including temperature, humidity, CO_2 concentration, total volatile organic compounds (TVOC), and light exposure, on the duration of light sleep. A low-cost device based on the Arduino platform was developed to continuously monitor these parameters during sleep. At the same time, a Xiaomi Mi Band 6 wristband was used to track sleep stages, including the duration of light sleep.

The originality of this work lies in the integration of real-time environmental data collection with consumer-grade sleep tracking in a real-world, single-subject setting. This method enables a detailed temporal correlation between environmental conditions and sleep parameters, which is often missing in large-scale population studies.

Preliminary findings indicate that the optimal room temperature for longer light sleep duration is approximately 18 °C. In contrast, humidity, CO_2, and TVOC levels did not show a clear direct effect on light sleep in this case study. Moreover, exposure to red light appeared to be associated with slightly shorter durations of light sleep, although no significant trends were observed for the influence of light spectrum in general.

2. Materials and Method

Arduino is an open-source hardware and software platform centred around a microcontroller capable of receiving and transmitting signals to and from its environment. It can interface with a wide range of devices, including those connected via the Internet, to control electronic systems [16].

A relay functions as an electromagnetic switch, allowing circuits to be turned on and off using a low-power signal. It is commonly employed when multiple circuits need to be controlled by a single input [17].

The DHT22 sensor is used for measuring both humidity and ambient air temperature. It transmits data through a single pin, while the remaining connections are dedicated to power and ground

Table 2: TVOC concentration levels and corresponding hygienic ratings [14].

Level	Hygienic Rating	Recommendation	TVOC [mg/m^3]	TVOC [ppb][8]
5 Unhealthy	Situation not acceptable	Intense ventilation necessary	10-25	2200-5500
4 Poor	Major objections	Intensified ventilation/ airing necessary	3-10	660-2200
3 Moderate	Some objections	Intensified ventilation recommended	1-3	220-660
2 Good	No relevant objections	Ventilation/airing recommended	>0.3-1	65-220
1 Excellent	No objections	Target value	<0.3	0-65

[18].

For air quality monitoring, the CCS811 sensor detects CO_2 equivalent levels and total volatile organic compounds (TVOC) using a proprietary algorithm based on a MOS gas sensor. Compared to traditional gas sensors, it offers lower power consumption, faster response times, and a more compact design [19].

2.1. Sleep monitoring

Sleep monitoring was conducted using the Xiaomi Mi Band 6, which records sleep duration and phases, including light sleep, deep sleep, REM, awakenings, and overall sleep quality. This data collection is enhanced by the device's BioTracker sensor, which provides continuous heart rate monitoring (24/7), automatic sleep tracking, and manual SpO_2 measurement.

Environmental conditions were monitored using a custom-built device containing multiple sensors and components. Humidity and temperature were measured using the DHT22 sensor, while CO_2 and TVOC levels were assessed using the CCS811 sensor. The system also included an Arduino Uno, a relay, a 12V fan, an SD card reader, and a control button, all enclosed within a compact peripheral housing designed to accommodate the sensors (Figure 1).

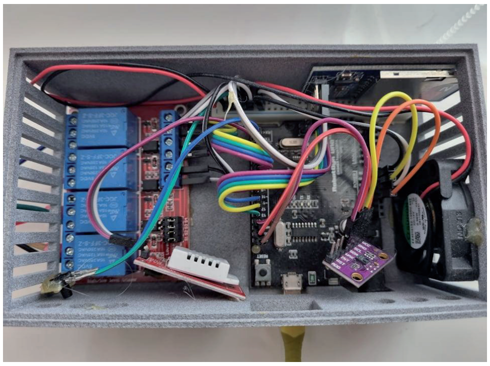

Figure 1: Compact monitoring device with integrated sensors (DHT22, CCS811), Arduino Uno, relay, 12V fan, SD card reader, and control button for environmental data collection.

For light exposure, SMD5050 LED strips were used. These high-performance LEDs offer broad application versatility and are available in both single-colour (e.g., cool white) and RGB variants. By combining red, green, and blue diodes, a wide spectrum of colours and shades can be generated via a control unit.

The enclosure was designed using the CAD software SolidWorks 2020 by Dassault Systèmes. It was then manufactured with an HP Jet Fusion 3D Printer. Ventilation openings were incorporated to allow airflow, along with dedicated slots for sensor cables and switch access (Figure 2).

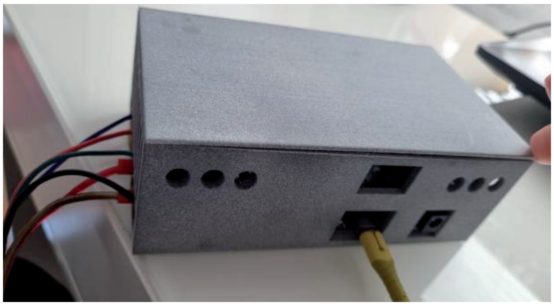

Figure 2: Acknowledgments3D-printed enclosure with ventilation openings and slots for sensor cables and switch access.

2.2. Measuring Sleep Quality

The Xiaomi Mi Band 6 smart bracelet was used to track sleep, specifically focusing on light sleep in relation to environmental conditions and different light spectra. The study examined how exposure to blue, red, green, or no light influenced light sleep duration. Data collection took place between 9 PM and 11 PM, with the monitoring system manually activated before the participant lay down in bed. The programmed setup ensured that the selected light colour remained on for 30 minutes before automatically turning off.

The participant stayed awake for 30 minutes before light exposure began. Afterward, sleep patterns were recorded, with a primary focus on light sleep. The session ended upon waking up, when the system was manually turned off. Sleep data was automatically logged by the smart bracelet.

2.3. Dataset Description

Data were collected across 21 nights in a real-world bedroom environment. For each night, the following environmental parameters were continuously monitored: temperature (°C), relative humidity (%), carbon dioxide (CO_2 in ppm), and total volatile organic compounds (TVOC in ppb). In addition, each night was assigned a specific light condition (e.g. darkness, red light, blue light, green light), which remained consistent throughout the night. An overview of the dataset is provided in Table 3, which summarizes basic descriptive statistics for the measured environmental variables.

Table 3: Summary statistics for the monitored environmental variables.

Parameter	Minimum	Maximum	Mean	Median	Standard Deviation
Temperature (°C)	15.3	24.2	19.6	19.4	2.5
Humidity (%)	43.0	65.2	54.3	54.1	6.4
CO_2 (ppm)	400	2568	1120.2	902.5	626.8
TVOC (ppb)	0	1956	149.7	127.0	565.5

3. Evaluation

A linear mathematical approximation was applied to the graph (Figure 3), from which the relationship between temperature and sleep quality cannot be determined precisely. However, the data indicate that sleep quality was higher in the central temperature range (17–21°C), while extreme values (below 17°C and above 21°C) were associated with poorer sleep. A nonlinear fitting approach could provide a more accurate representation of this trend by capturing potential fluctuations more effectively.

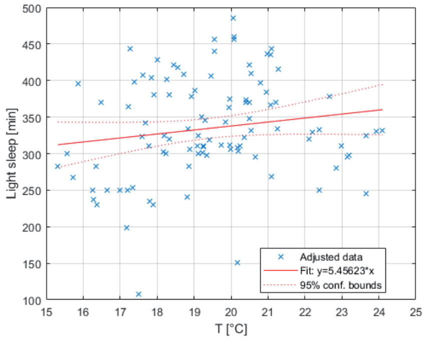

Figure 3: Relationship between light sleep and temperature.

The analysis of light sleep and humidity shows no noticeable effect based on the measured data. The graph does not indicate any clear correlation (Figure 4), suggesting that humidity levels did not significantly influence light sleep duration.

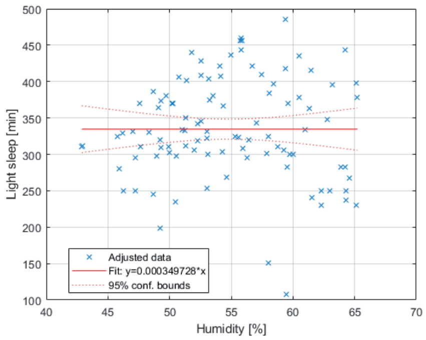

Figure 4: Relationship between light sleep and humidity.

The analysis of light sleep and CO_2 levels shows no observable impact based on the measured data (Figure 5). The graph does not indicate any clear correlation between CO_2 concentration and light sleep duration, suggesting that CO_2 levels did not significantly affect this sleep stage.

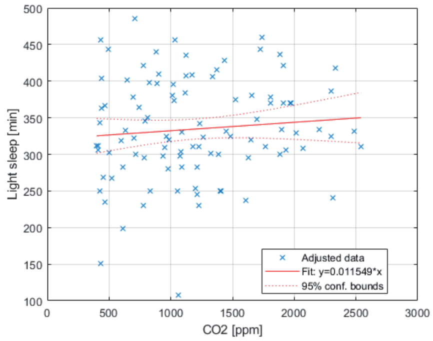

Figure 5: Relationship between light sleep and CO_2 levels.

The analysis of light sleep and TVOC levels indicates no observable impact based on the measured data (Figure 6). The graph does not show any clear correlation between TVOC concentration and light sleep duration, suggesting that TVOC levels did not significantly influence this sleep stage.

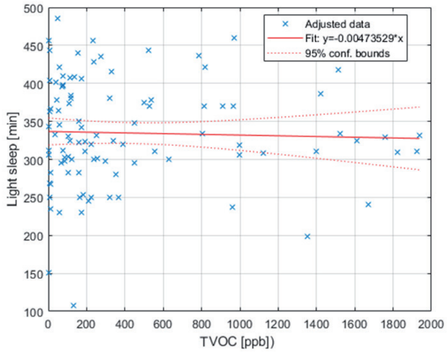

Figure 6: Relationship between light sleep and TVOC levels.

The analysis of sleep duration across different light conditions reveals that the best sleep quality was achieved in complete darkness (Figure 7). Light sleep duration under blue and green light was similar, showing no significant difference between these two spectra. However, the shortest light sleep duration was recorded under red light exposure.

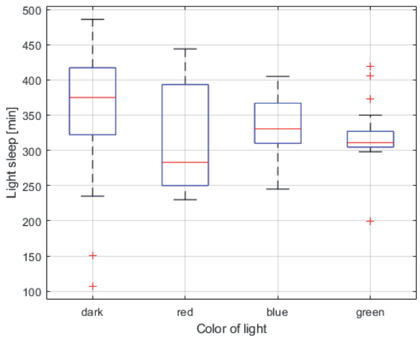

Figure 7: Relationship between light exposure and light sleep duration.

Notably, when analysing light sleep specifically, the data indicate that the colour spectrum of light had no measurable impact. This suggests that while different wavelengths may influence overall sleep duration, they do not significantly alter the time spent in light sleep. These findings highlight the potential role of light exposure in regulating sleep patterns, particularly in deeper sleep stages, while light sleep remains unaffected by spectral variations.

4. Results and Discussion

This case study provides insights into how environmental conditions may influence the duration of light sleep. The analysis focused on five main factors: temperature, humidity, CO_2 concentration, TVOC levels, and light exposure.

To assess the potential influence of temperature on sleep, a linear regression model was applied. This method was chosen due to the limited dataset size and the need for a simple, interpretable model. As this was a single-subject case study with only 21 nights of data, more complex models such as support vector regression or locally estimated scatterplot smoothing were avoided to reduce the risk of overfitting.

The results suggest that light sleep duration tended to be longer within a temperature range of 17–21 °C. At temperatures outside this range, particularly below 17 °C or above 21 °C, a decline in sleep duration was observed. Although the linear model does not capture potential nonlinear effects, it provided an initial approximation of the relationship, indicating that temperature may have a measurable impact on light sleep quality.

In contrast, humidity, CO_2 concentration, and TVOC levels did not show a clear relationship with light sleep duration. The recorded values fluctuated within typical indoor ranges, and no statistically significant correlations were found. These results suggest that, at least within the tested limits, air quality parameters may not be critical determinants of light sleep duration.

Regarding light exposure, the longest light sleep duration was recorded under conditions of complete darkness. Blue and green light produced similar results, while red light exposure was associated with the shortest light sleep periods. This finding implies that red light might slightly disrupt light sleep maintenance. However, overall, no strong or consistent relationship was observed between specific light wavelengths and the duration of light sleep. This may indicate that the light spectrum has a more pronounced influence on deeper sleep stages rather than light sleep alone.

5. Conclusions

This study examined how various environmental factors, including temperature, humidity, CO_2 levels, TVOC concentration, and light exposure, affect light sleep duration. The results suggest that temperature has the most noticeable impact, with the best sleep quality occurring within the 17–21 °C range. Among the analysed air quality parameters, humidity, CO_2, and TVOC levels did not significantly influence light sleep duration, indicating that these factors may not play a critical role in sleep regulation under the tested conditions.

The analysis of light exposure revealed that complete darkness resulted in the longest light sleep duration, while red light exposure was associated with the shortest. No significant differences were found between blue and green light, suggesting a comparable effect on this sleep phase. Overall, spectral variations did not show a distinct influence on light sleep duration, which implies that their effects may be more pronounced in other stages of sleep.

Since this study was conducted on a single subject, the results should be interpreted with caution. Individual differences in sleep behaviour and sensitivity to environmental stimuli may have contributed to the observed outcomes. To draw more general conclusions, future research should include a larger group of participants to better understand how environmental conditions influence sleep across diverse individuals.

Further studies should also explore the role of specific light wavelengths in sleep architecture, particularly their impact on transitions between sleep stages and their long-term effects on overall sleep quality.

In addition, the application of nonlinear regression techniques such as regression trees, LOESS, or support vector regression should be considered in future work. These methods may help detect more complex relationships or threshold effects that simple linear models are unable to capture, particularly when examining environmental variables like air quality components or categorical light conditions.

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