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REVIEW ARTICLE

A Path to Better Sleep and Circadian Health: Optimizing and Personalizing Indoor Lighting

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Circadian rhythms play a crucial role in the regulation of sleep, metabolism, and cognitive function. However, they are highly sensitive to disturbances caused by irregular indoor lighting, especially exposure to blue light at night. This review explored the impact of indoor lighting on circadian and sleep health by analyzing trends in light exposure, socioeconomic disparities, and the prioritization of economic efficiency over health in modern lighting design. Significant variations in individual circadian rhythms present a challenge in creating standardized lighting environments. To address this issue, a review suggested the development of personalized lighting systems that use advanced sensors to monitor and respond to the circadian phase of each individual. By dynamically adjusting light intensity, wavelength, and timing, these systems can better align with personal biological clocks, promote optimal sleep and overall health, and advance the concept of truly human-centric lighting environments.

Keywords: Circadian rhythms; Indoor lighting; Personalized lighting; Sleep health

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INTRODUCTION

Circadian rhythms, natural internal clocks aligned with the daily rotation of the Earth, play crucial roles in the regulation of a wide range of biological functions in all forms of life [1]. In humans, these rhythms are governed by a set of core clock genes, including *Arntl*, *Per*, *Cry*, and *Nr1d1*. These genes are part of transcriptional-translational feedback loops, which are responsible for creating intrinsic oscillations that persist close to a 24-hour cycle [2]. This circadian mechanism, which is precise enough to sustain a nearly 24-hour cycle without external cues, orchestrates key physiological functions such as sleep, metabolism, and cognitive processes [3]. However, its stability is vulnerable to internal challenges, such as aging and psychiatric disorders, as well as external factors. Irregular lighting conditions in indoor environments can significantly disrupt natural rhythms. Exposure to inappropriate artificial light, particularly pervasive blue light at night, has been identified as a critical factor that contributes to circadian misalignment and subsequent health issues, necessitating careful management of light exposure to protect circadian and sleep health [4,5].

In this review, we discuss several key aspects of indoor lighting to understand its impact on sleep and circadian health. First, we examined trends in indoor lighting exposure over recent decades, assessing whether there has been a general increase and how this varies between affluent and less-developed countries. This discussion outlines the temporal evolution and socioeconomic disparities in light exposure and their implications for circadian and sleep health. Second, we explore the underlying motivations for the design and implementation of modern indoor lighting systems, suggesting a potential emphasis on economic benefits over individual health concerns. Third, we reviewed the range of inter-individual variations in circadian phases to determine whether a uniform lighting approach could effectively accommodate these differences. Fourth, we analyze the critical factors that should be considered from a health perspective when designing indoor lighting, distinguishing between general and individual-specific factors. By exploring these aspects, this study aimed to deepen our understanding of how indoor lighting influences sleep patterns and circadian health.

GLOBAL TRENDS IN INDOOR LIGHTING: INCREASING USAGE AND INEQUALITIES

The pervasive use of artificial light, both indoors and outdoors, has increased globally over the past century, resulting in a significant expansion of indoor lighting in residential spaces [6]. This rapid growth in artificial light environments has significantly increased human exposure to bright settings, even at night [7]. Although precise comparative data on artificial light usage from 1950 to 2020 remain elusive, it is evident that artificial light usage in common environments has increased sharply. The widespread increase in indoor lighting is closely related to socioeconomic development. Consequently, significant disparities in artificial light usage persist even within the same contemporary era. Developed megacities, such as New York, Seoul, and Tokyo, boast an extensive artificial lighting infrastructure, which contributes to luminous landscapes that illuminate the night sky. In contrast, regions with smaller populations, such as rural areas (e.g., Gangwon Province in South Korea) or less urbanized areas (e.g., Florida in the United States), tend to embrace a more nature-centric lifestyle with relatively limited exposure to artificial light. In these areas, nights often remain darker, characterized by a gentle glow of moonlight and sparse artificial illumination. These disparities highlight the substantial variation in indoor lighting patterns influenced by regional and socioeconomic factors.

Traditionally, various health problems have been observed to be more common in less medically developed eras or countries with slower socioeconomic development [8]. However, the spread of artificial light and the resultant increase in light exposure during nighttime hours can negatively impact health from sleep and circadian health perspectives. Interestingly, several recent studies have indicated that insomnia symptoms are less prevalent in rural settings than in urban settings [9-12]. These findings suggest that such disparities in artificial light environments may contribute to variations in sleep patterns and quality between urban and rural populations [13]. More research is warranted on the impact of artificial light on sleep and circadian health in different living environments, highlighting the need for interdisciplinary collaboration between medicine, public health, and urban planning to comprehensively address these complex issues.

MODERN LIGHTING SYSTEMS: ECONOMIC EFFICIENCY OVER CIRCADIAN HEALTH?

As the global emphasis on energy conservation and sustainability intensifies, various technological advances have been made to reduce the electrical energy used for lighting [14]. The history of lighting development, which began with the invention of incandescent bulbs, has evolved to include the use of light-emitting diodes and organic light-emitting diodes with the development of the next generation of lighting technologies. These advances have primarily focused on optimizing light efficiency and creating brighter illumination at lower costs and for extended durations. Although some studies have explored the relationship between lighting and aspects such as performance, productivity, and creativity, sleep and circadian health have been overlooked in the development process [15-18]. Optimizing lighting for these health aspects often sacrifices economic efficacy because it involves dimming lights, adjusting wavelengths, or varying brightness according to the time of day [19]. Furthermore, the simplistic notion that "turning off lights could be sufficient" has also hindered the development of lighting systems that consider sleep and circadian health. Considering that natural light typically decreases between 6 PM and 8 PM, most exposure to artificial light at night is artificial and can negatively affect sleep quality and cause circadian misalignment [20]. Recent studies in the expanding field of neuroarchitecture suggest that adjusting the intensity, wavelength, and timing of lighting to be more human-centric and nature-like can positively affect perceived well-being, sleep quality, and circadian health [21-24]. Therefore, in the coming era, the value of creating a human-centric lighting environment that considers sleep and circadian health should be emphasized beyond mere economic efficacy. Achieving this will require technological innovation, regulatory enhancements, and strategic policy decisions.

INTER-INDIVIDUAL CIRCADIAN VARIATION: CHALLENGES FOR STANDARDIZED HUMAN-CENTRIC LIGHTING ENVIRONMENT AND REASONS FOR PERSONALIZATION

What does this specifically mean in creating a human-centric lighting environment? From an evolutionary biology perspective, in which the human body has been optimized over time to match natural environments, a human-centered lighting environment can be one with no artificial lighting that relies solely on natural light. However, the development of lighting devices has significantly extended the hours during which humans can be active and work, which are intricately linked to the complex structures of modern society. Therefore, a world without artificial lighting would be unrealistic. Therefore, it is essential to consider the meaning of creating a human-centric lighting environment in the presence of artificial light. First, it is important to determine whether standardized characteristics exist in human-centric lighting environments. Typically, when analyzing lighting characteristics, factors such as light intensity, wavelength, flicker, and intensity variation are considered [25-27]. Additionally, one of the most important factors that affect these lighting characteristics is timing. In other words, it is not just the absolute properties of light that matter, but also how these properties interact with the internal circadian clock of an individual. This challenge lies in the fact that the internal circadian clock can vary significantly between individuals. The characteristics of light generally interact with an individual's rest-activity phase, which, although having an average phase, exhibits considerable inter-individual variation. For example, in two actigraphy studies conducted by our research team in patients with chronic insomnia and cognitive impairment, the rest-activity phase showed a normal distribution with large standard deviations [28,29]. This means that the remaining activity phases of two random individuals could easily differ by nearly 4 hours. In other words, inter-individual circadian variation is a significant factor that complicates the design of standardized human-centric lighting environments.

Given that the internal circadian clock exhibits an average phase and considerable individual variability, the future of lighting design must move toward creating personalized lighting environments. To achieve this, it is essential to take advantage of the rapidly advancing sensor technologies to monitor an individual's physiological state, particularly its circadian rhythm, which is essential [30]. These sensors provide real-time data on an individual's circadian phase, allowing the development of lighting systems that dynamically interact with the unique biological clock of each individual. These systems would adjust light intensity, wavelength, and timing to align with an individual's circadian rhythm, thus optimizing sleep and overall health. This approach not only addresses the challenge posed by inter-individual circadian variation, but also represents a significant advancement toward truly human-centric lighting environments that cater to personalized needs.

CONCLUSION

In conclusion, managing the impact of indoor lighting on circadian and sleep health is essential in modern society, where artificial lighting is ubiquitous. Circadian rhythms, which are regulated by core clock genes and are sensitive to light exposure, are vital for various physiological functions. However, the widespread use of artificial light, particularly at night, disrupts natural rhythms. Addressing this issue requires a shift toward personalized lighting environments. Using advanced sensor technologies to monitor an individual's circadian phase can help develop dynamic lighting systems that adjust light intensity, wavelength, and timing to align with each person's unique biological clock. This approach not only mitigates the adverse effects of artificial light, but also promotes optimal sleep and overall health, paving the way for truly human-centric lighting environments.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Availability of Data and Material

Data sharing not applicable to this article as no datasets were generated or analyzed during the study.

Author Contributions

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