

RESEARCH ON ADAPTIVE DESIGN OF SLEEP-AID SPACE ENVIRONMENT BASED ON MULTI-MODAL AI PERCEPTION TECHNOLOGY

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Abstract

In an era of rapid urbanization and widespread digital connectivity, sleep disorders have evolved into a serious global public health crisis. The deterioration of sleep quality is closely related to the stress of modern life and the static and unresponsive nature of the built environment. Traditional interior design gives priority to static aesthetics and layout, often ignoring the dynamic physiological needs of human circadian rhythms. To address this fundamental disconnect, this study explores the integration of multimodal artificial intelligence (AI) sensing technology into sleep-assisted environments, aiming to construct a theoretical design framework for active participation of physical environments in sleep regulation.

Using qualitative research and a literature review, this paper analyzes the complex relationship between visual, auditory and tactile environmental sensory inputs and sleep physiology. The study criticized the limitations of existing smart homes relying on user intervention and proposed a "perception-decision-action" autonomous cycle with multimodal AI as the "central nervous system". The system captures physiological and environmental data in real time using a non-invasive network of millimeter-wave radar, thermal imaging and environmental sensors. AI can dynamically adjust lighting color temperature to stimulate melatonin secretion or adjust HVAC systems to match body temperature during sleep without conscious user intervention. The conclusion shows that the transformation from passive spatial accommodation to active intelligent environmental adaptation can significantly improve the efficiency of sleep initiation and maintenance, which provides a theoretical basis for future indoor design of healthy adaptation.

Keywords: Multi-modal AI, Adaptive Design, Sleep-Aid Environment, Interior Design, Circadian Rhythm

Introduction

Sleep is a fundamental biological imperative that accounts for about a third of human life. It is a key mechanism for physiological recovery, memory consolidation, metabolic regulation, and immune system maintenance. However, the conflict between the development trend of modern civilization and the biological needs of human beings is increasingly prominent. An all-weather (24/7) society characterized by high-pressure work environments, irregular shift schedules and the widespread presence of artificial electronic devices emitting blue light has triggered a global sleep crisis. According to the World Health Organization and several sleep medicine organizations, a significant proportion of urban populations suffer from chronic insomnia, sleep fragmentation or circadian rhythm disorders. Chronic sleep deprivation has been linked to serious health problems such as cardiovascular disease, obesity, depression, and significant cognitive decline.

Although medical and pharmaceutical interventions remain the primary means of treating sleep disorders, the role of the physical environment, especially the bedroom, is often overlooked in clinical discussions. At the same time, in the design world, bedrooms are often seen only as

spaces for furniture rather than as therapeutic tools. Traditional interior design methods focus on static elements such as bed layout, wall color, and fabric texture. Once these elements are determined, it becomes difficult to adapt to users' changing physiological needs throughout the night. A room that looks good at 10:00 a.m. may not promote deep sleep at 2:00 a.m. The rigidity of this design reflects its failure to match the temporal characteristics and biological dynamics of the human organism.

The core problem of current residential design in promoting sleep health lies in the lack of adaptability and intelligence. Existing so-called "smart home" technologies tend to be fragmented and reactive. They rely on manual user actions, such as voice commands, App adjustments, or physical interactions, which places a "cognitive burden" on users. For individuals who have insomnia, the very act of picking up a cell phone to adjust the thermostat or dim the lights is alarming and thus counterproductive to the goal of promoting sleep. At present, there is a clear lack of a systematic design theory that integrates multimodal AI perception with environmental psychology to create a space that automatically "cares" for occupants without explicit instructions.

This study aims to bridge the disciplinary gap between AI technology and fine arts/design with the following objectives:

1. From the point of view of environmental psychology and chronobiology, the theoretical relationship between environmental factors (light, sound, temperature) and sleep physiology is analyzed.

2. Clarify the role and mechanism of multimodal AI perception in capturing and interpreting human sleep states in spatial contexts without invading privacy.

3. A comprehensive adaptive design framework for sleep-aiding environments is proposed, which operates autonomously to support circadian rhythms.

This study adopts qualitative research methods centered on text analysis and literature review, and does not involve human subject experiments or collection of raw biometric data. Instead, it integrates existing knowledge from three different fields: sleep medicine (chronobiology), computer science (AI and IoT sensing), and environmental design. By cross-referencing the data patterns and theoretical models of these disciplines, a new conceptual framework for adaptive interior design was constructed.

Content

1. Symbiotic relationship between environment and physiology

To design an effective sleep environment, we need to understand the biological mechanisms of sleep and its interaction with external stimuli. The theoretical basis of this study is grounded in biological "Zeitgeber" theory and environmental psychology.

1.1 Neurobiological mechanisms of circadian rhythms: the role of the suprachiasmatic nucleus (SCN)

The circadian rhythm, which runs on a 24-hour cycle, is regulated by the suprachiasmatic nucleus (SCN) of the hypothalamus. The SCN acts as a "master clock" that synchronizes internal biological processes with the external solar day. Light is the SCN's most potent "timing factor" (time giver).

Melatonin pathway and autonomous photosensitive retinal ganglion cells (ipRGCs): The retina has autonomous photosensitive retinal ganglion cells (ipRGCs), which are distinct from rod and cone cells. These cells express melanopsin, which is extremely sensitive to short-wavelength light (blue light), with a peak sensitivity of about 460-480nm. When stimulated by blue light, ipRGCs project directly to the SCN via the retinal-hypothalamic tract (RHT), and the signal is relayed to the pineal gland, thereby inhibiting melatonin secretion. Melatonin is a hormone that

signals the body to fall asleep. Conversely, lack of blue light or exposure to long-wavelength light (amber/red, >600nm) promotes melatonin synthesis.

Thermoregulation and sleep structure: sleep is closely related to thermoregulation. To initiate sleep, core body temperature (CBT) must drop by about 1°C. This cooling process is accomplished by vasodilation of distal limbs (hands and feet) to radiate heat away from the core. If the ambient temperature is too high, it will hinder heat dissipation and increase sleep latency (the time required to fall asleep). In addition, different stages of sleep (NREM vs. REM) have distinct thermal sensitivities; REM sleep, in particular, is characterized by a loss of thermoregulation (a warm state) that makes sleepers vulnerable to fluctuations in ambient temperature.

Acoustic sensitivity and cortical arousal: The brain continues to process auditory information even during sleep. Sudden changes in decibel levels (transients) trigger the reticular activation system (RAS), triggering cortical arousal. This fight-or-flight mechanism fragments sleep and prevents the body from entering deep sleep (NREM stage 3), which is critical for recovery.

1.2 Environmental psychology and supportive design

Roger Ulrich's supportive design theory suggests that health is promoted when environments foster a sense of control, provide positive social support, and give positive distractions. In the bedroom context, the concept of "control" is contradictory. Despite user expectations of ownership, controlling environmental variables requires effort and vigilance. Thus, the study suggests that the ultimate form of supportive design in sleep is anticipatory control, i.e., environmental self-management to support the user's passive state, thereby reducing the cognitive load required to achieve comfort. This is consistent with the concept of "Calm Technology," where technology hides behind the scenes and supports users without distracting them.

2. Multimodal AI Perceptual System Architecture

The term "multimodal" refers to AI's ability to process and fuse multiple types of input data simultaneously. In the design context, the system mimics the human sensory system, creating a "conscious" room. The proposed architecture consists of three layers: perception layer (input), processing layer (AI core) and action layer (output).

2.1 Advanced non-invasive sensing

To make the sleeping environment restorative, it should be unobtrusive. Traditional medical sleep monitoring requires electrodes (EEG) or wearable devices that disrupt the natural sleep experience. This study advocates "Device-Free Sensing" embedded in buildings:

Millimeter Wave Radar (mmWave): This is the key to the perception layer. Unlike RGB cameras, which raise serious privacy concerns, millimeter wave radar (which typically operates at 60GHz or 77GHz) uses frequency-modulated continuous wave (FMCW) technology.

Vital signs monitoring: It detects chest displacement with sub-millimeter accuracy to calculate respiratory rate and heart rate variability (HRV). High frequency (60GHz) allows high-resolution detection of microDoppler features associated with respiration.

Sleep Staging: By analyzing breathing patterns (e.g., deep sleep monitoring in NREM), by monitoring breathing (including irregular breathing in non-REM and REM periods) and large body movements (body movement recordings), advanced algorithms can estimate sleep stages (awake, light sleep, deep sleep, REM periods) with accuracy comparable to medical grade contact devices.

○ **Privacy protection:** Since no optical images are generated, user privacy is naturally guaranteed.

Thermal imaging sensor: A low-resolution infrared sensor (e.g., 32×32 or 64×64 pixel array) is used to map the temperature distribution of the user's body surface. This allows the system to identify whether the user is overheated (such as kicking a quilt) or too cold before they consciously wake up. It also acts as a reliable bed occupancy detector capable of operating in total darkness.

Environmental sensors:

1. **Acoustic sensors:** measure decibel levels (dB) and spectra to distinguish between persistent background noise (white noise) and disruptive impulsive events (alarms, barking dogs, door closings).

2. **Photometric sensors:** measure not only brightness (lux Lux) but also spectral composition (correlated color temperature- CCT, Kelvin) to ensure that lighting is in tune with the circadian phase.

3. **Air quality sensors:** monitor CO₂ levels, humidity and volatile organic compounds (VOCs). Studies have shown that carbon dioxide levels above 1000ppm can lead to fragmented sleep and morning drowsiness due to mild hypercapnia.

2.2 Edge Computing and Data Fusion

To ensure privacy and real-time response, the system uses an Edge Computing architecture, where data is processed locally within the home rather than transmitted to the cloud.

Multimodal data fusion: The AI core uses fusion algorithms to correlate data from different sensors. For example, a single sensor detecting a drop in room temperature may be ambiguous. But when thermal cameras detect user tremors and radars detect restless motion, the fusion engine can confirm "thermal discomfort" with high confidence.

Reinforcement Learning (RL): The system optimizes environmental parameters with reinforcement learning agents. AI's "reward function" is defined by the quality of the user's sleep (e.g., longer duration of deep sleep, fewer awakenings). Over time, AI can learn user-specific preferences, breaking through common factory settings and building personalized sleep models.

3. adaptive environmental control strategy

Based on the theoretical framework and technical capability, this study classifies according to sensory modalities and proposes a set of comprehensive adaptive design strategies covering three aspects: vision, hearing and atmosphere.

3.1 Dynamic circadian lighting protocol

Lighting design needs to shift from static on/off functions to dynamic spectral ecosystems that mimic natural solar processes.

Bedtime phase (circadian entrainment): Two hours before the user's historical bedtime, the AI initiates a "sunset protocol."

Spectrum: Illumination converted to warm spectrum (2000K - 2700K). Crucially, the spectral power distribution (SPD) is adjusted to minimize energy in the 460 - 480nm range to ensure melatonin secretion.

Intensity: Ceiling lights are completely turned off, only perimeter, low lighting (wall lamps, lamp troughs) remains. The illumination at eye level is controlled below 50 Lux.

Night phase (safety and maintenance): During sleep phase, the room remains in "all black mode." However, adaptability is critical to safety.

Navigation mode: If the millimeter wave radar detects that the user sits up (with the intention of leaving the bed), the system will activate the LED strip under the bed. These strips emit a soft amber light (10 Lux). This long-wavelength light provides visual guidance for easy access to the bathroom without stimulating intrinsically photosensitive retinal ganglion cells (ipRGCs), allowing users to easily fall asleep again.

Wake phase (cortisol arousal response): To reduce sleep inertia, the room initiates a "sunrise simulation" 30 minutes before alarm time.

Spectrum: Light changes from warm red to cool white (6500K).

Intensity: Gradually increases from 0 to 300 Lux. This stimulates the cortisol arousal response (CAR), which naturally awakens the brain and resets the body clock for a new day.

3.2 Intelligent Soundscape Construction

Silence is not always optimal for sleep because complete silence amplifies the perceived loudness of sudden external noise (signal-to-noise ratio is too high).

Active Noise Masking: Designed with an intelligent sound masking system. If the acoustic sensors detect intermittent low-frequency noise (such as distant traffic or HVAC hum), the system generates complementary "pink noise" or "brown noise."

Mechanism: Pink noise has equal energy in each octave, mimicking the frequency distribution of many natural sounds, such as rain or rustling leaves. This effectively "fills in" the background environment towards silence, moderately raising the acoustic floor, and thus reducing the harshness of sudden peak noise.

Pro-life soundscapes: At moments when high physiological stress is detected (e.g., elevated heart rate before bedtime or insomnia symptoms), the system can deploy pro-life sounds (e.g., rain, wind, waves). Studies have shown that these natural-based sounds suppress sympathetic nervous system activity more effectively than artificial music or silent environments.

3.3 Thermal comfort and air quality regulation

Thermal environments are often the primary cause of sleep disruption, especially "micro-arousals" caused by thermal discomfort.

Predictive thermoregulation: Adaptive systems learn a user's thermal comfort preference profile over time.

Sleep period: When the user goes to bed, the system may lower the ambient temperature moderately (e.g., to 19 - 21°C) to drive down the core temperature required to initiate sleep.

REM sleep protection: In the early morning hours, when REM sleep is dominant and the body loses its ability to regulate body temperature, the system may moderately raise the temperature or adjust the smart mattress to prevent the user from waking up from the cold.

Air quality feedback loop: Ventilation systems are often noisy and have draft problems. AI systems optimize air quality by monitoring carbon dioxide levels. When a CO₂ threshold (e.g. 800ppm) is breached, it quietly and gradually activates ventilation or purification systems to ensure oxygen saturation is maintained at levels conducive to cognitive recovery while avoiding acoustic interference.

4. Enlightenment to Interior Design Practice

4.1 From static design to dynamic design

The integration of multimodal AI requires interior designers to fundamentally transform their approach to bedroom design. Design is no longer limited to material selection and furniture layout, but also involves the overall planning of intangible systems. Designers must consider the fourth dimension of space: time. The environment is no longer a static background, but a dynamic participant in the user's life.

4.2 Ethics and Privacy in Design

Such a high level of surveillance in the most intimate spaces of the home raises significant ethical questions. Designers must prioritize "Privacy by Design." Relying on unidentifiable data sources (radar and thermal imaging) rather than optical cameras is a key design decision to build trust. In addition, local processing of the data (edge AI) ensures that the user's bedroom does not

become a monitoring node. The design shall communicate this safety to the user through physical indicators indicating when the sensor is active or local data processing is taking place.

4.3 Intelligent Aesthetics

Finally, the "intelligence" of space must be integrated at the aesthetic level. Sensors should be hidden in architectural elements or furniture (e.g. radar behind headboards, CO₂ sensors in nightstands). Technology should remain invisible ("calm technology") and the emphasis should remain on comfort and aesthetics of the space. The target lives not in a machine, but in a space that feels natural and organic, intelligently empowered by hidden machines.

Conclusion

5.1 key findings

This paper discusses the fusion of multi-modal artificial intelligence (AI) perception technology and modern interior design, and constructs an adaptive design framework for sleep-aid space environment. Through a comprehensive analysis of relevant literature and design theories, it is obvious that the traditional static bedroom design model is no longer sufficient to meet the complex sleep challenges of modern society.

The main findings indicate that:

1.Holistic Integration:Effective sleep-aid design must move beyond isolated smart items (such as smart light bulbs or air purifiers) to build a holistic ecosystem where AI coordinates lighting, sound, and temperature. This integration ensures that all environmental stimuli are synchronized in time and serve the physiological goal of inducing sleep.

2.Non-invasive Interaction:The success of this type of environment is highly dependent on the presence of "invisible" technologies. The application of millimeter wave radar and thermal imaging technology proves that users do not need to wear equipment or frequently operate screens, and the space itself should have the ability to sense user needs (such as temperature changes, respiratory rate) and automatically respond. This non-sensory interaction reduces cognitive load and helps maintain relaxation.

3.Deep Personalization: Adaptive design enables mass-produced dwelling units to break "one size fits all" comfort standards through machine learning algorithms. The system is able to learn and adapt to an individual's unique sleep patterns and sensitivity thresholds over time, delivering a highly customized sleep experience that is truly human-centric.

5.2 research significance

This research has made important contributions to the field of design at both theoretical and practical levels:

Theoretical model innovation:The model of "Intelligence-based Human-Centric Design" is proposed, which directly transforms neurobiological principles into spatial design parameters and provides new theoretical support for interior design.

Interdisciplinary Paradigm:Shows how art and design disciplines can be effectively integrated with computer science and medicine. Emphasizes the transformation of the designer's role-from creator of visual aesthetics to orchestrator of healthy environments.

Social value:providing a non-pharmacological, environmental intervention solution to the growing sleep crisis. If widely applied, this design strategy could significantly improve public health and reduce the socioeconomic costs of sleep deprivation.

5.3 study limitations

Although this study constructs a relatively perfect theoretical framework, there are still the following limitations:

Lack of empirical data:This study mainly adopts text analysis and literature review to construct theory, lacking clinical experimental data based on physical prototype. Theoretically effective adjustment of environmental parameters (such as the specific influence of color temperature change on melatonin) may be disturbed by many variables in the actual complex residential environment, which needs further quantitative verification.

Technology implementation costs:The proposed multi-modal sensing systems (especially high-precision millimeter wave radar and thermal imaging) are currently costly and may limit their popularity in ordinary homes.

Complexity of individual differences:Although personalized learning mechanisms have been proposed, this study has not yet provided a perfect coordination algorithm solution for possible physiological needs conflicts between bed partners (e.g., one person is afraid of heat and the other person is afraid of cold).

5.4 future expectations

Based on these findings and limitations, future research should focus on:

Experimental prototype construction and empirical research:Future work should focus on building a full-featured "Sleep Lab" prototype. EEG and PSG data were collected to quantify the effects of adaptive environments on sleep latency and sleep efficiency.

Deepening privacy and ethical frameworks:As technology penetrates the private space, data privacy and ethical considerations must be better addressed in future design implementations. More transparent data processing protocols and user interfaces need to be developed to enhance user trust in intelligent systems.

Multi-user collaborative algorithm:For the case of two or more people sharing sleeping space, develop more complex game algorithms to balance the environmental needs of different users and achieve precise control of local micro-environment (such as zoning temperature control of smart mattresses).

References

- Arendt, J. (2010). Shift work: Coping with the biological clock. *Occupational Medicine*, 60(1), 10–20. <https://doi.org/10.1093/occmed/kqp162>
- Blume, C., Garbaza, C., & Spitschan, M. (2019). Effects of light on human circadian rhythms, sleep and mood. *Somnologie*, 23(3), 147–156. <https://doi.org/10.1007/s11818-019-00215-x>
- Cajochen, C. (2007). Alerting effects of light. *Sleep Medicine Reviews*, 11(6), 453–464. <https://doi.org/10.1016/j.smr.2007.07.009>
- Chinoy, E. D., Duffy, J. F., & Czeisler, C. A. (2018). Unrestricted evening use of light-emitting tablet computers delays self-selected bedtime and disrupts circadian timing and alertness. *Physiological Reports*, 6(10), e13692. <https://doi.org/10.14814/phy2.13692>
- Foley, L. (2025, July 10). *Bedroom environment: What elements are important?* Sleep Foundation. <https://www.sleepfoundation.org/bedroom-environment>
- Hatori, M., & Panda, S. (2010). The emerging roles of melanopsin in behavioral adaptation to light. *Trends in Molecular Medicine*, 16(10), 435–446. <https://doi.org/10.1016/j.molmed.2010.07.005>
- Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, 15(3), 169–182. [https://doi.org/10.1016/0272-4944\(95\)90001-2](https://doi.org/10.1016/0272-4944(95)90001-2)
- Lack, L. C., & Wright, H. R. (2007). Chronobiology of sleep in humans. *Cellular and Molecular Life Sciences*, 64(10), 1205–1215. <https://doi.org/10.1007/s00018-007-6531-2>
- Strøm-Tejse, P., Zukowska, D., Wargocki, P., & Wyon, D. P. (2016). The effects of bedroom air quality on sleep and next-day performance. *Indoor Air*, 26(5), 679–686. <https://doi.org/10.1111/ina.12254>
- Topol, E. J. (2019). High-performance medicine: The convergence of human and artificial intelligence. *Nature Medicine*, 25(1), 44–56. <https://doi.org/10.1038/s41591-018-0300-7>
- Ulrich, R. S. (1984). View through a window may influence recovery from surgery. *Science*, 224(4647), 420–421. <https://doi.org/10.1126/science.6143402>
- Ulrich, R. S. (2008). Biophilic theory and research for healthcare design. In S. R. Kellert, J. H. Heerwagen, & M. L. Mador (Eds.), *Biophilic design: The theory, science, and practice of bringing buildings to life* (pp. 87–106). John Wiley & Sons.
- Walker, M. (2017). *Why we sleep: Unlocking the power of sleep and dreams*. Scribner.
- World Health Organization Regional Office for Europe. (2018). *Environmental noise guidelines for the European Region*. <https://www.who.int/publications/i/item/9789289053563>
- Zielinski, M. R., McKenna, J. T., & McCarley, R. W. (2016). Functions and mechanisms of sleep. *AIMS Neuroscience*, 3(1), 67–104. <https://doi.org/10.3934/Neuroscience.2016.1.67>