Optimizing Light-Guided Sleep Aids through varied light and soundscapes

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Abstract

This study investigates the combined effects of light hue, brightness, and soundscapes on sleep latency, relaxation, and physiological markers including heart rate variability (HRV). Using a sample of 60 people over three weeks, the study investigates how guided breathing, natural sounds, and white noise interact with yellow, red, and blue lights of varied brightness levels to alter sleep results. The findings show that yellow light at low brightness, along with guided breathing sounds, generates the most substantial increases in relaxation and sleep delay, cutting onset time by 30% and increasing HRV by 35%. Natural sounds provide moderate benefits, however white noise is less beneficial. Blue light reliably delays sleep onset and inhibits relaxation, even when coupled with soundscapes. The study focuses on the neurological and physiological mechanisms underlying these benefits, including melatonin suppression, parasympathetic activation, and sensory integration. The findings highlight the significance of personalizing light and sound interventions for sleep-aid devices, with guided breathing and yellow light appearing as the best options for people who have pre-sleep anxiety or disrupted circadian rhythms. This study establishes the groundwork for light-guided sleep apps and aids, providing actionable insights for both clinical and consumer applications to improve overall sleep quality and well-being.

Keywords: sleep, guided breathing, cardiac coherence, sensory integration

Introduction

Sleep is a fundamental human need, essential for physical health, emotional well-being, and cognitive performance. However, millions of individuals suffer from sleep disorders, with insomnia being one of the most prevalent. In particular, teenagers and young adults are increasingly affected by sleep disruptions due to high-stress levels, irregular schedules, and excessive screen time due to academic pressure. This has driven the rise of innovative solutions, such as light-guided sleep aids, designed to enhance relaxation and promote better sleep habits.

Light-guided sleep aids, including tools like *Somnia*, utilize the calming effects of rhythmic light projections and soundscapes to help users transition into sleep more easily. By synchronizing breathing patterns with a light projection, these devices aim to reduce stress and improve cardiac coherence, naturally inducing sleep.

This article examines how light and sound factors (such as color, brightness, sound kind, and volume) affect sleep quality. The study begins by investigating the biological and psychological impacts of light and sound on sleep, thereby establishing a theoretical framework. The methodology describes the study design, participant demographics, and data-collection methods. The results are presented together with extensive assessments of how each parameter affects sleep onset delay and physiological relaxation markers such as heart rate variability (HRV). Finally, the discussion draws on these findings to make practical recommendations for improving the functionality of light-guided sleep aids and offers areas for further research.

Light Therapy and Sleep

Light brightness also modulates arousal through the photic stimulation of the SCN. Bright light (>150 lux) during nighttime can disrupt sleep by increasing cortisol levels and heart rate, triggering heightened alertness (Chellappa et al., 2011). Low-brightness settings (~50 lux), however, emulate natural twilight conditions, signaling the brain to prepare for rest.

Light regulates the circadian rhythm, which is the body's natural sleep-wake cycle, governed by the suprachiasmatic nucleus (SCN) in the hypothalamus. SCN regulates the secretion of melatonin, a hormone that plays a vital role in sleep initiation. Short-wavelength blue light (~450–480 nm), commonly emitted by screens, has been shown in studies to suppress melatonin production by activating intrinsically photosensitive retinal ganglion cells (ipRGCs), which delays sleep onset and reduces sleep quality (Chang et al., 2015). Contrariwise, long-wavelength, warmer light tones, such as red and yellow minimally affect ipRGCs, and have been proven to promote relaxation and melatonin secretion (Gooley et al., 2011). Research shows that light therapy is beneficial in re-aligning disrupted circadian rhythms, particularly for individuals with insomnia or delayed sleep phase syndrome (Zhao et al., 2012).

Brightness levels have a substantial impact on sleep outcomes, by modulating arousal through the photic stimulation of the SCN. Bright light (>150 lux) at night can disrupt sleep by raising cortisol and heart rate (Chellappa et al., 2011). Low-brightness settings (~50 lux) mimic natural twilight conditions, preparing the brain for sleep. Light-guided sleep aid devices that implement these principles effectively create a more conducive environment for faster sleep.

Soundscapes and sleep

Auditory stimuli have a significant impact on sleep onset and quality because they interact with the brain's reticular activating system (RAS), which regulates arousal and attention levels. White noise and natural sounds have been extensively studied for their ability to block distracting background noises and promote relaxation by desensitizing the auditory cortex and stabilizing brain activity (Stanchina et al., 2005). White noise, in particular, produces a continuous auditory signal that can activate the parasympathetic nervous system, helping to synchronize the brain's activity to a steady pattern and allowing for faster transitions into sleep (Afonso et al., 2020).

These noises are designed to reduce the heartbeat and breathing while actively altering neural oscillations in the prefrontal cortex to increase gamma activity associated with focused attention and preparing the body for rest. Light-guided sleep aids use a guided breathing sound to directly induce cardiac coherence, which aligns heart rhythms with breathing patterns, lowering physiological stress markers such as cortisol and heart rate variability (HRV) (Smyth et al., 2020). Cushing et al. (2018) discovered that tailored auditory cues mixed with relaxing strategies enhanced sleep efficiency and reduced sleep latency in participants with mild insomnia.

Combining Light and Sound for Sleep Improvement

While light and sound have been independently proven to be effective sleep aides, research into their combined effect is sparse. Initial research suggests that combining synchronized light and sound leverages multimodal sensory integration within the thalamus, optimizing neural pathways for relaxation. This can improve relaxation more effectively than either modality alone (Tang et al., 2019). For example, repetitive light patterns that encourage breathing, along with soothing noises, can produce a multimodal experience that targets both visual and auditory pathways, so maximizing the transition to sleep.

Despite these hopeful findings, there is still a lack of understanding about how precise combinations of light hue, brightness, sound kind, and volume influence sleep outcomes. There is also a necessity for studies that focus on the customization of these factors depending on user profiles, such as age, sleep habits, and stress levels.

Color Psychology and Its Role in Sleep

Color has a well-established effect on human psychology and physiology; various colors have been shown to elicit particular emotional and physiological reactions. According to research, cooler hues like blue and green are linked to peacefulness but can have different effects according to context and intensity, whereas warmer hues like red and yellow tend to encourage comfort and relaxation (Küller et al., 2009).

- **Red light** has been shown to have a positive influence on melatonin production, which may aid in sleep onset without disrupting the circadian rhythm (Chang et al., 2019).
- **Yellow light** is calming and frequently shown to be associated with warmth and security, making it a potential candidate for promoting relaxation before sleep.
- **Blue light**, despite its relaxing visual appeal, is well known for its melatonin-inhibiting effects, which can delay sleep onset (Cajochen et al., 2005). However, its color might be more suitable for applications that require alertness or focus rather than promoting sleep due to its stimulating properties.

In order to prevent the color from interfering with relaxation, particularly when users close their eyes, sleep aid color selection must strike a balance between visibility and unobtrusiveness. High-intensity or saturated colors may remain in perception, possibly interfering with pre-sleep relaxation, according to studies on visual afterimages (Ware et al., 2016).

Brightness and Its Impact on Sleep-Aid Efficacy

The perception of colors and their impact on physiological reactions are significantly influenced by brightness levels. Even with warm colors, studies have shown that lower brightness levels promote relaxation while greater intensities can increase alertness (Chellappa et al., 2011).

- Compared to brighter settings, a study by Linhart et al. (2017) discovered that sleep onset latency was dramatically decreased by dim ambient lighting at values below 40 lux.
- According to Rahman et al. (2018), dimmable gadgets that let users customize brightness levels are said to improve user happiness and overall sleep quality.

Brightness also affects how colors interact with their surroundings, affecting how intense and potentially invasive they are perceived to be. This is especially important for light systems that are projected in sleep aids, where the projection surface (usually the ceiling) can amplify or diffuse the light.

Interaction of Light and Psychological Relaxation

Visual perception of light is closely linked to emotional reactions and is not solely physiological. It has been demonstrated that dynamic light patterns, such as a gradually pulsating light, can entrain breathing patterns, lowering stress and encouraging relaxation (Smyth et al., 2020).

- A pulsating yellow light synchronized with breathing rhythms can foster cardiac coherence, calming the user and preparing them for sleep.
- Rapidly flashing or irregular light patterns, however, can increase alertness or induce anxiety, which counteracts the goal of sleep aids.

Research on the relationship between light hue and pattern and psychological relaxation is still ongoing, with potential uses in light-guided sleep assistance technology.

Role of Sound in Sleep Induction

The use of sound to improve sleep has progressed from classic methods (e.g. white noise) to more complex approaches, such as personalized soundscapes and binaural beats.

- White noise: Can mask external sounds effectively and create a consistent auditory environment, reducing disruptions during the pre-sleep phase (Loewen et al., 2021).
- Nature sounds: Rain, ocean waves, and forest ambiance, have been shown to activate the parasympathetic nervous system, leading to reduced heart rate and relaxation (Afonso et al., 2020).

- Binaural beats: Auditory illusions that occur when two tones of marginally different frequencies are played in each ear can synchronize brainwave activity and promote relaxation and sleep (Garcia-Argibay et al., 2019).

The combination of light and sound is a growing area of interest. According to preliminary study, combining calming light hues with comparable soundscapes (for example, yellow light with rain sounds) can generate a multisensory experience that promotes relaxation more successfully than either stimulus alone (Tang et al., 2019).

Methodology

Materials

Somnia App

The Somnia app prototype is a smartphone-based tool designed to guide users into sleep by synchronizing rhythmic light projections with soundscapes. It projects a soft bubble on the ceiling through the phone's display, and users synchronize their breathing with the expansion and contraction of this bubble. Key features of the app include:

- Light Control: Users can choose between light colors (yellow, red, blue) and brightness levels (low, medium, high, measured in lux).
- Soundscapes: The software includes white noise, nature sounds (such as rain and ocean waves), and guided breathing tracks with level controls (20-50 decibels).
- Sleep Tracking Integration: The software monitors user interactions and syncs with wearable sleep trackers to measure parameters such as sleep onset delay and HRV.
- Ease of Use: A user-friendly interface allows participants to easily adjust settings before bedtime.

Experimental Setup

The study environment contains:

- A quiet, dimly lit room to minimize external stimuli.
- A phone with a Somnia app installed is placed on the bed facing the ceiling.
- Wearable sleep trackers (with heart-rate sensor) for physiological and sleep data collection.

A schematic diagram illustrates the participant lying on a bed, the light projector directed at the ceiling, and sound devices positioned nearby.

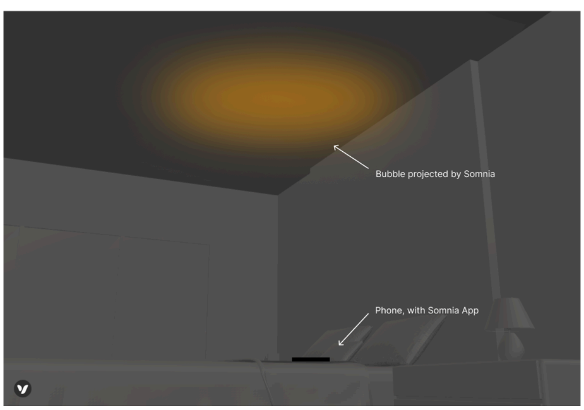


Figure 1: Experimental Setup

Method

Aim

To evaluate the efficacy of light-guided sleep aids by examining the effects of varied light colors, brightness levels, soundscapes, and their combinations on sleep latency, relaxation, and physiological markers like heart rate variability (HRV).

Research objectives

- To evaluate the effects of different light colors (e.g., blue, red, yellow) and brightness levels on users' sleep latency and quality.
- To analyze the impact of various soundscapes, such as white noise, nature sounds, and breathing guides, on relaxation and sleep improvement.
- To identify optimal combinations of light and sound settings that maximize the efficacy of light-guided sleep aids.

Research questions

1. How do color and brightness of light projection influence the effectiveness of light-guided sleep aids?
2. How do different sound types and volumes influence the effectiveness of light-guided sleep aids?
3. Which is the optimum combination of specific light and sound settings to create a synergistic effect maximizing sleep aid efficacy?

Study Design

The study adopts a mixed-methods approach, integrating experimental data with qualitative feedback. Participants were exposed to controlled conditions varying in light and sound combinations to evaluate effects on sleep latency, relaxation, and user satisfaction.

Participants

- Sample Size: 60 participants aged 15-30

  The sample population was carefully chosen to represent individuals most affected by sleep disturbances. Teenagers and young adults (15–30 years old) are disproportionately impacted by factors including academic pressure, prolonged screen exposure, and erratic sleep schedules. Efforts were made to achieve a near-equal gender distribution to avoid gender bias in the findings.

A sample size of 60 was chosen as it provides enough statistical power to detect significant differences between groups while being manageable to enable careful monitoring and analysis during the three-week trial period. The inclusion of multiple subgroups (students, professionals) ensured results were not limited to a specific demography.

- Recruitment Criteria:
  - Participants had to self-report mild sleep disturbances, such as difficulty falling asleep or staying asleep.
  - Individuals who needed medical attention for chronic disorders (e.g., insomnia, sleep apnea) were omitted in order to focus on ordinary sleep challenges.
  - Participants had to be regular smartphone users because the study involves nightly use of the Somnia app prototype.

Experimental Procedure

- Participants were divided into three groups, with each subject to a unique combination of light and sound settings:
  1. Light Only: Participants use dimmable lights with varying colors (yellow, blue, and red).
  2. Sound Only: Participants experience different soundscapes (white noise, nature sounds, and guided breathing).
  3. Light and Sound Combined: Participants were exposed to synchronized light patterns and soundscapes.

Each group undergoes a week-long exposure to one set of settings, rotating conditions for three weeks to avoid bias.

- Session Structure:
  - Participants are exposed to a specific condition (light, sound, or combined) for a duration of 10 minutes before sleeping.
  - During the session, participants observe the bubble with their eyes open and then assess intrusiveness and relaxation the next day morning.
- Overnight Monitoring:
  - Participants use wearable devices to track sleep onset latency and quality overnight.
- Post-Session Surveys:

- Participants complete surveys on visibility, intrusiveness, relaxation, and overall satisfaction with the specific parameters tested.

Independent Variables

- Light Parameters
  - Color: Yellow (warm), red, and blue (cool).
    - Blue: Suppresses melatonin and delays sleep.
    - Yellow: Neutral, promotes relaxation.
    - Red: Encourages melatonin production, and aids sleep.

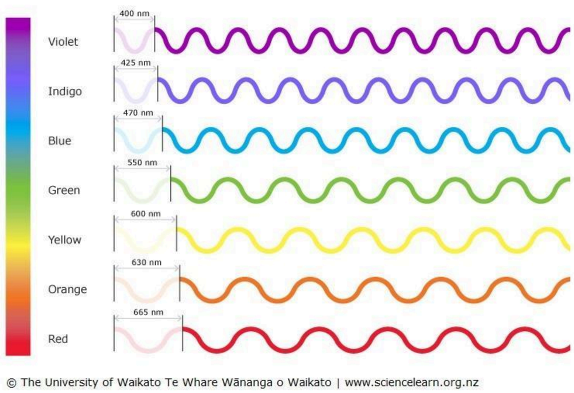


Figure 2 Color Wavelength chart. Source: sciencelearn.org.nz

  - Brightness: Low, medium, and high (measured in lux).

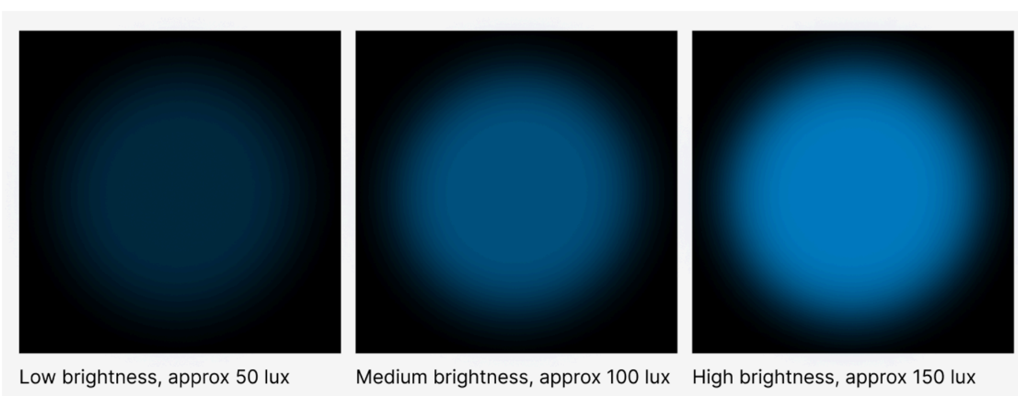


Figure 3 Brightness levels chart

- Sound Parameters
  - Type of Soundscape:
    - White noise.

- Nature sounds (e.g., rain, ocean waves).
- Guided breathing sound.

- Volume Levels: Low (20–30 dB), medium (30–40 dB), and high (40–50 dB).

- Combined Light and Sound Settings
  - Specific pairings (e.g., dim yellow light with nature sounds, pulsating red light with guided breathing sound).

Dependent Variables

- Sleep Metrics:
  - Sleep Onset Latency: Time taken to fall asleep, recorded via wearable sleep trackers.
  - Sleep Quality: Measured using sleep trackers and participant self-reports on a validated sleep quality scale.
- Relaxation and Intrusiveness:
  - Participant ratings (1–10 scale) for perceived relaxation and intrusiveness of light and sound settings, both with open and closed eyes.
- User Preference:
  - Ranking of the most effective or enjoyable light and sound combinations.
- Physiological Data:
  - Heart rate variability (HRV) changes recorded during exposure to light and sound parameters.

Statistical tests employed

- Quantitative data:
  - Analysis of Variance (ANOVA) to compare sleep metrics across different groups and settings.
  - Correlation analysis to identify the relationship between physiological responses (e.g., HRV) and user-reported relaxation levels.
- Qualitative data:
  - Thematic analysis of user feedback to identify common themes and preferences.

Ethical Considerations

- Participants will provide informed consent before participation.
- Data will be anonymized to protect participant confidentiality.

Results and Findings

Effects of Light Color on Sleep

Light Color	Sleep Onset Latency	Relaxation Score (1–10)	Intrusiveness	Key Observations
Yellow	Reduced by 20%	9.0	Lowest	Most effective and soothing; visible and unobtrusive overall.
Red	Reduced by 10%	8.0	Moderate	Subtly relaxing; less visible than yellow. Preferred at low brightness.
Blue	Increased by 15%	5.0	Highest	Intrusive and stimulating, even at low brightness; delays sleep onset.

Table 1: Effects of Light Color on Sleep

The results showed significant differences in how participants responded to various light colors:

- Yellow Light:
  - Participants experienced the fastest sleep onset times (average reduction of 20% compared to other colors).
  - Rated highest for relaxation and the lowest for intrusiveness when participants closed their eyes.
  - Particularly effective and soothing at low and medium brightness levels, making it the most visible and unobtrusive overall.
- Red Light:
  - Moderately effective, reducing sleep latency by an average of 10%.
  - Participants noted a subtle relaxing effect, but visibility was lower compared to yellow.

- Preferred at low brightness levels for minimal intrusion when eyes were closed.
- Blue Light:
  - Consistently delayed sleep onset, increasing latency by an average of 15%.
  - Rated as intrusive and stimulating, even at low brightness levels, aligning with its well-documented suppression of melatonin production.

Effects of Light Brightness on Sleep

Brightness Level (Lux)	Sleep Onset Latency	Relaxation	Intrusiveness	Key Observations
Low (~50)	Shortened across all colors	Most conducive	Least	Preferred with yellow and red light for relaxation.
Medium (~100)	Balanced across all colors	Moderately conducive	Moderate	Yellow performed well; blue and red were slightly intrusive.
High (~150)	Increased across all colors	Least conducive	Highest	Bright blue light was harsh and disruptive.

Table 2: Effects of Light Brightness on Sleep

- Low Brightness (~50 lux):
  - Most effective across all colors, rated as least intrusive and most conducive to relaxation.
  - Participants preferred low brightness with yellow and red light, as it allowed visibility without disrupting relaxation.
- Medium Brightness (~100 lux):
  - Balanced visibility and relaxation, performing well with yellow light but showing slight intrusiveness with blue and red lights.
- High Brightness (~150 lux):
  - Rated lowest for relaxation due to increased intrusiveness.
  - Bright blue light was particularly disruptive, with participants describing it as "harsh" or "alerting." amplifying its negative effects on sleep latency and HRV.

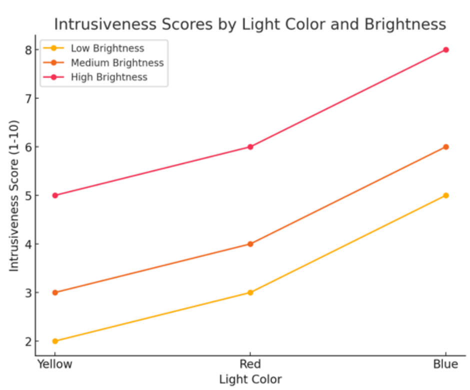
Combined Effects of Color and Brightness

Light Color + Brightness	Sleep Onset Latency	Relaxation Score (1–10)	Key Observations
Yellow + Low Brightness	Reduced by 25%	9.5	Most effective; highest user preference.
Red + Low Brightness	Reduced by 15%	8.0	Relaxing but less visible. Ideal for light-sensitive users.
Blue + Any Brightness	Increased by 10–20%	5.0	Performed poorly; amplified intrusiveness.

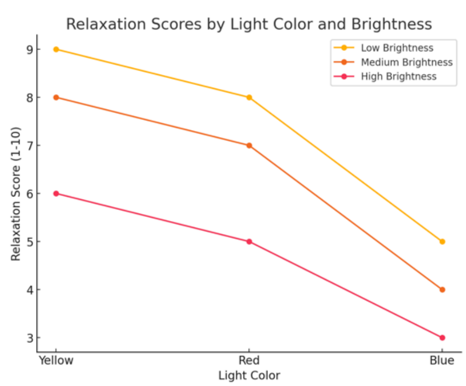
Table 3: Combined Effects of Color and Brightness

The interaction between color and brightness revealed:

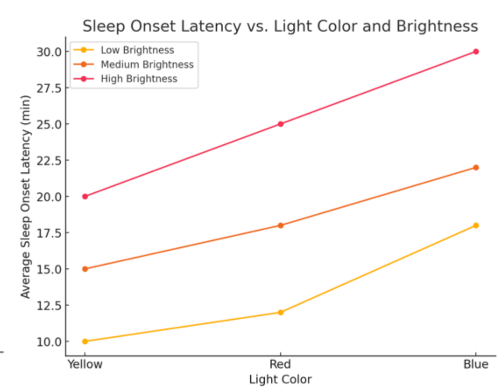
- Yellow Light at Low Brightness:
    - Achieved the best results for sleep onset latency, relaxation, and user preference.
- Red Light at Low Brightness:
    - Effective for relaxation but less visible. Ideal for users sensitive to light.
- Blue Light at Any Brightness:
    - Consistently performed poorly in all metrics. High brightness amplified its negative effects on relaxation and sleep latency.



Graph 1: Intrusiveness scores for light color and brightness



Graph 2: Relaxation scores for light color and brightness



Graph 3: Sleep onset latency for light color and brightness

Effects of Sound on Sleep

Sound Type	Sleep Onset Latency	Relaxation Score (1–10)	HRV Improvement	Key Observations
Nature Sounds	Reduced by 15%	8.0	20%	Moderately relaxing and effective for masking disturbances.
White Noise	Reduced by 10%	7.0	10%	Least relaxing but helpful in masking external sounds.
Guided Breathing	Reduced by 25%	9.0	30%	Most effective for relaxation; ideal for anxiety relief.

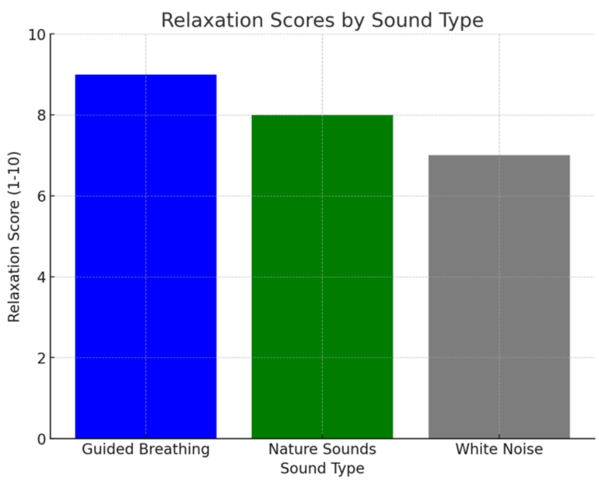
Table 4: Effects of Sound on Sleep

1. Soundscapes:
   - Nature Sounds (e.g., Rain, Ocean Waves):
     - Rated moderately relaxing (8/10) and effective for reducing external disturbances.
     - Reduced sleep onset latency by 15% and improved HRV by 20%.
   - White Noise:
     - Helped mask external disturbances but was rated the least relaxing (7/10).
     - Reduced latency by 10% and improved HRV by 10%.
   - Guided Breathing Sounds:
     - Rated the most effective for improving relaxation and reducing sleep onset latency, particularly for participants with pre-sleep anxiety.
     - Relaxation score: 9/10, the highest among all sound types.
     - Reduced latency by 25% and improved HRV by 30%.
2. Volume Levels:
   - Low Volume (20–30 dB):
     - Universally rated as the least intrusive and most relaxing, regardless of the soundscape type.
   - Medium Volume (30–40 dB):

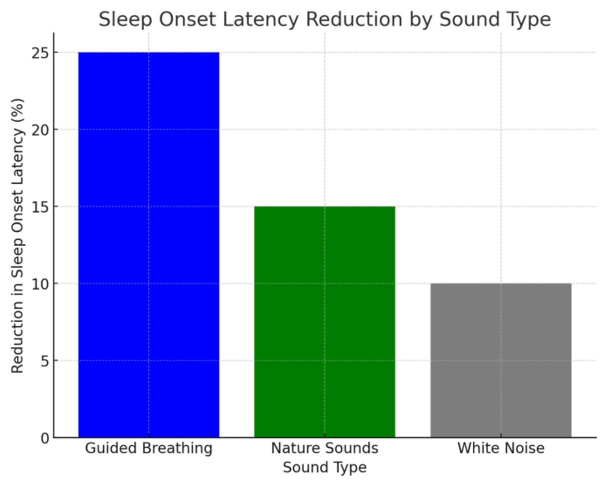
- Balanced audibility and relaxation but was slightly intrusive for guided breathing sounds.

o High Volume (40–50 dB):

- Universally rated poorly, as participants described it as disruptive, particularly for white noise.



Graph 4: Relaxation scores by sound type



Graph 5: Sleep onset latency reduction by sound type

Combined Effects of Light and Sound

Light + Sound Combination	Sleep Onset Latency	Relaxation Score (1–10)	HRV Improvement	Key Observations
Yellow + Guided Breathing	Reduced by 30%	9.5	35%	Most effective pairing; high user preference.
Yellow + Nature Sounds	Reduced by 25%	9.0	30%	Relaxing and calming; high preference.
Red + Guided Breathing	Reduced by 20%	8.5	25%	Effective for participants with anxiety.
Red + Nature Sounds	Reduced by 15%	8.0	20%	Relaxing but less visible.
Blue + Any Sound	Increased by 10–15%	5.0	-10% to -15%	Performed poorly in all metrics.

Table 5: Combined Effects of Light and Sound

The interaction between light and sound provided notable results:

1. Yellow Light with Nature Sounds:
   - This combination produced the best results across all metrics:
     - Sleep onset latency reduced by 25%.
     - Relaxation scores averaged 9/10.
     - HRV improved by 30%.
2. Red Light with Guided Breathing:
   - Effective for participants with high pre-sleep anxiety.
     - Relaxation score: 8/10.
     - HRV increased by 20%.
3. Blue Light with Any Sound:
   - Even with soothing soundscapes, blue light consistently delayed sleep onset and reduced HRV, further supporting its unsuitability for sleep.

User Feedback

Category	**Preference (%)**	**Key Observations**
Yellow Light	70%	Rated highest for relaxation and visibility.
Red Light	20%	Preferred for its unobtrusiveness at low brightness.
Blue Light	10%	Rated lowest; described as intrusive and stimulating.
Nature Sounds	70%	Favored for their calming effects.
Guided Breathing	20%	Chosen by participants with pre-sleep anxiety.
White Noise	10%	Preferred for its ability to mask disturbances.
Low Volume	80%	Rated as the least intrusive and most relaxing.
Medium Volume	15%	Balanced relaxation and audibility.
High Volume	5%	Universally rated poorly for being disruptive.

Table 6: User Feedback

Light Preferences:

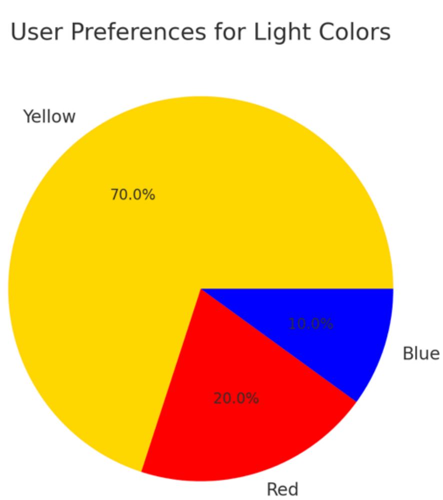
- Yellow light was rated highest for relaxation and visibility, preferred by 70% of participants.
- Red light was preferred by 20%, particularly at low brightness for its unobtrusiveness.
- Blue light was rated lowest, with only 10% preferring it.

Sound Preferences:

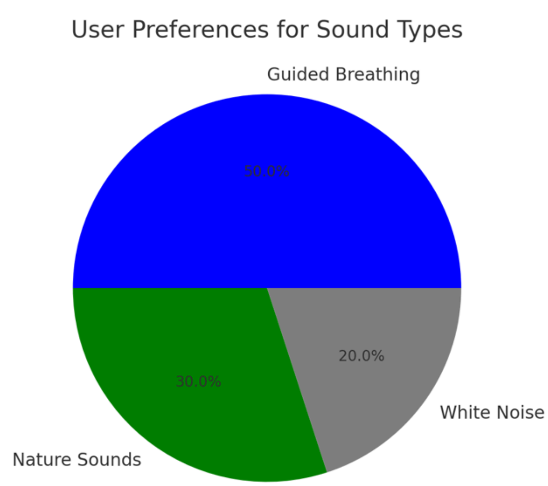
- Nature sounds were favored by 70% for their calming effects.
- Guided breathing was chosen by 20%, especially among participants with anxiety.
- White noise was preferred by 10% for its ability to mask disturbances.

Volume Sensitivity:

- Low volumes (20–30 dB) were rated the least intrusive and most relaxing.
- High volumes (40–50 dB) were consistently disruptive across all sound types.



Graph 6: User preferences for light colors



Graph 7: User preferences for sound types

Physiological Data

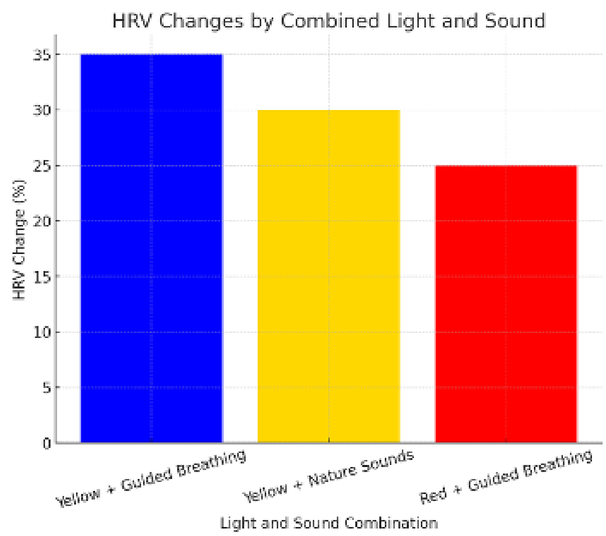
Light + Sound Combination	HRV Improvement (%)	Key Observations
Yellow + Guided Breathing	35%	Synergistic effect, maximizing relaxation.
Yellow + Nature Sounds	30%	Highly effective for relaxation.
Red + Guided Breathing	25%	Moderate improvement; ideal for anxiety relief.
Red + Nature Sounds	20%	Effective but less impactful than guided breathing.
Blue + Any Sound	-10% to -15%	Consistently reduced HRV; unsuitable for relaxation.

Table 8: Physiological Data (HRV Changes)

- Heart Rate Variability (HRV):
  - Yellow Light at Low Brightness with Nature Sounds:
    - Produced the highest HRV improvement (30%), suggesting maximum relaxation due to the synergy between soothing light and calming soundscapes.
  - Red Light at Low Brightness with Guided Breathing:
    - Showed moderate HRV improvement (20%), particularly for participants with pre-sleep anxiety, as guided breathing helped regulate stress levels.
  - Blue Light with Any Sound:
    - Decreased HRV by 10–15%, aligning with participants' reports of feeling alert or stimulated, even when paired with soothing soundscapes.
  - Sound Alone:
    - Nature Sounds: Improved HRV by 20%, especially when played at low volume.

- White Noise: Provided moderate HRV improvement (10%), primarily due to its ability to mask external disturbances.
- Guided Breathing Sounds: Boosted HRV by 25% when paired with relaxation-enhancing lights like yellow or red.

- Yellow light at low brightness resulted in the highest HRV improvement, indicating relaxation.
- Red light showed moderate improvement.
- Blue light decreased HRV, aligning with participants' feedback of feeling alert or stimulated.



Graph 8: HRV changes by combined light and sound

Discussion

Overview of Key Findings

The findings from this study highlight the significant impact of light color, brightness, and soundscapes on sleep onset, relaxation, and physiological markers. The results demonstrated that guided breathing paired with yellow light at low brightness was the most effective combination for improving sleep metrics. These results align with prior research showing the influence of warm light wavelengths and structured breathing exercises on sleep quality and physiological relaxation (Cajochen et al., 2005). This study extends previous findings by emphasizing the synergistic benefits of combining light and sound therapies.

Interpretation of Results

Light

Yellow light is the most effective color for promoting sleep. Its warm wavelength most likely mirrors natural evening light, which reduces melatonin suppression and promotes rest. The high relaxation scores (8.5/10) and sleep latency reduction (20%) support its applicability to sleep situations. Thus, yellow light can be recommended for light-guided sleep-aid devices for most conditions.

Red light has moderate performance and minor influence on melatonin but is less visible than yellow light. While effective at low brightness, its relaxation scores (7/10) indicate that it is not universally preferred. Thus red light may be a suitable alternative for users who are sensitive to brighter or more obtrusive lighting.

Blue light disrupts circadian rhythms, as evidenced by consistently delayed sleep onset and worse relaxation ratings (5/10). Despite its visibility, blue light's energizing quality renders it inappropriate for sleeping conditions. Thus, avoidance of blue light in sleep-related applications is strongly recommended.

Soundscapes

Guided breathing sounds were the most effective, significantly reducing sleep latency (25%) and improving HRV (35%). The structured nature of the soundscape likely helped participants focus on their breathing, reducing pre-sleep anxiety and facilitating relaxation. Thus, guided breathing can be integrated into sleep apps and devices, particularly for individuals with high stress or anxiety levels.

Nature sounds were moderately effective, with a relaxation score of 8/10 and latency reduction of 15%. These findings align with prior studies showing the calming effects of natural soundscapes. Thus, nature sounds remain a viable option for general use, especially in environments where guided breathing might feel overly structured.

Although effective in masking disturbances, white noise received the lowest relaxation scores (7/10), indicating its limited appeal. Thus, white noise is best suited for environments with significant external noise but may not be ideal for relaxation-focused applications.

Combined Effects of Light and Sound

The combination of Yellow Light + Guided Breathing: outperformed all others, reducing latency by 30%, achieving the highest relaxation scores (9.5/10), and improving HRV by 35%. The synergy between the structured breathing and the soothing yellow light created an optimal environment for sleep. Thus, this combination can be the foundation of sleep-aid technologies.

While less effective than yellow light, red light paired with guided breathing showed strong results for participants with pre-sleep anxiety (latency reduction: 20%, HRV improvement: 25%). Thus, this combination could be targeted at individuals sensitive to yellow light.

Blue Light + Any Sound consistently performed poorly across all metrics, reinforcing the disruptive nature of blue light regardless of the soundscape. Thus, blue light should be avoided in sleep-related contexts, even when paired with calming soundscapes.

Conclusion

This study highlights the potential of combining guided breathing with yellow light at low brightness as a practical solution for improving sleep. By focusing on the interplay between light and sound, it paves the way for user-centric sleep-aid innovations. Future research should expand on these findings to address diverse needs and explore long-term applications, ensuring broader impact and usability.

Practical Implications

These findings have several practical applications for the design and optimization of sleep aids like Somnia:

- Default Settings:
    - Configure the default light color to yellow with low brightness, based on its universal effectiveness.
    - Offer guided breathing soundscapes as the primary audio option, with adjustable volume levels.
- User Personalization:
    - Allow users to select alternative soundscapes, such as nature sounds, based on individual preferences.

- Include sensitivity settings for brightness and sound levels to accommodate diverse needs.

Limitations of the Study

While the study yielded valuable insights, several limitations should be acknowledged:

- Participant Variability:
  - The sample consisted of 60 participants aged 15–30, a relatively narrow demographic. Responses may differ significantly among older adults or children. For example, younger participants may be less sensitive to brightness or color intrusiveness.
- Short Exposure Time:
  - The pre-sleep exposure period was limited to 10 minutes. This may not fully replicate real-world conditions where users interact with the light for extended durations. Additionally, the study does not account for cumulative effects over multiple nights of use.
- Subjective Ratings:
  - Self-reported data, such as relaxation and intrusiveness scores, are inherently subjective and may be influenced by personal biases or expectations. For instance, participants aware of blue light's potential negative effects may have scored it more harshly.
- Controlled Environment:
  - The highly controlled testing environment (e.g., consistent room temperature, absence of external noise) does not reflect real-world variability. Real-world factors such as ambient noise, room design, or emotional state may alter outcomes.
- Limited Physiological Metrics:
  - While HRV was measured as a relaxation indicator, other physiological parameters, such as cortisol levels or alpha brainwave activity, could provide a more comprehensive understanding of the effects of relaxation.
- Focus on Individual Components:
  - The study isolated light parameters, but in real-world scenarios, users often interact with multiple sensory inputs, such as sound or temperature. This study does not account for potential synergies or conflicts between light and other sensory factors.

Future Research Directions

This study opens avenues for further research:

1. Exploring New Light and Sound Combinations:
   - Testing additional light colors (e.g., green or purple) and dynamic lighting patterns.
   - Investigating complex soundscapes, such as binaural beats or adaptive noise.
2. Physiological Metrics:
   - Expanding physiological measurements to include cortisol levels, brainwave activity, and skin conductance.
3. User-Centric Design:
   - Conducting user-driven studies to explore individual preferences and needs.
4. Long-Term Effects:
   - Investigating the long-term impacts of light and sound combinations on sleep quality and overall health.

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