

Review

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[Shanshan Song](#), Misbah Mehrab, Zohaib Tahir, Kathleen A Garrison, Stephen Ziskind*

Posted Date: 3 November 2025

doi: 10.20944/preprints202511.0041.v1

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Review

Sensory-Based Sleep Interventions: Light, Sound, and Temperature as Therapeutic Tools

Running title: Sensory-based interventions for sleep

Shanshan Song ¹, Misbah Mehrab ¹, Zohaib Tahir ¹, Kathleen A Garrison ^{1,2}
and Stephen Ziskind ^{1,*}

¹ Sleep Sanity, LLC, 251 Larue, Lexington, KY 40517

² Department of Psychiatry, Yale University School of Medicine, 1 Church Dr, #730 New Haven, CT 06511

* Correspondence: sziskind@sleep-sanity.com

Abstract

Sleep is an essential physiological process that is influenced not only by mental and behavioral functions, but also by the surrounding sensory conditions. Emerging but mixed evidence shows that sensory-based interventions, such as light, sound, and temperature, can aid sleep for some individuals, though effects vary by population and outcome. Light therapy influences circadian rhythms and has clinical applications for sleep-wake disorders. Auditory interventions including white, pink, and brown noises, autonomous sensory meridian response, music, and natural sounds can mask environmental disruption, though they are most effective when tailored to the individuals' sensory profiles. Ambient temperature control particularly in populations facing night sweats or menopause also influences the initiation and maintenance of sleep. However, how these modalities can be integrated together to increase adherence and success in individual patients have not been extensively reported. In this narrative review, we highlight recent research on light therapy, auditory intervention, and thermal regulation in improving sleep health, and suggest integration of these modalities to supplement Cognitive Behavioral Therapy for Insomnia. While evidence quality varies considerably, integrating sensory approaches may complement established behavioral therapies and broaden accessible, non-pharmacological options for improving sleep health. Continued research is needed to determine optimal combinations, timing, and individual responsiveness.

Keywords: sensory-based interventions; light therapy; circadian rhythms; auditory intervention; thermoregulation; Cognitive Behavioral Therapy for Insomnia (CBT-I)

1. Introduction

Sleep is an essential biological process that supports nearly every aspect of physical and mental health [1], by regulating mood, cognition, immune function, and cellular repair [2,3]. Yet, 37% of U.S. adults report insufficient sleep (<7 hours nightly), 50-70 million have chronic sleep disorders, and 1 in 3 adults experience daytime sleepiness [4,5]. Further, about 10% meet criteria for insomnia disorder, with another 20% experiencing occasional symptoms [6], and about 80% of adults with clinically significant sleep apnea remain undiagnosed [7]. Insufficient sleep not only affect individuals' cognitive performance and emotional regulation in daily life, but also increases the risk for depression, anxiety, cardiovascular disease, and metabolic disorders [8–10]. A deeper understanding of sleep mechanisms and the development of effective solutions for sleep health are urgently needed not only to improve life quality for affected individuals but also to mitigate the broader social and economic burdens.

Traditional behavioral approaches aim to modify maladaptive sleep habits and cognitive patterns [11], while pharmacologic treatments primarily modulate neurotransmitter systems to induce sedation or reduce arousal [12]. While both can be effective, behavioral interventions require adherence, and pharmacological approaches may show reduced efficacy over time in some individuals [12]. Growing evidence highlights sensory-based interventions, including light therapy, auditory stimulation, or thermoregulation, as accessible, non-pharmacological tools to improve sleep [13–15]. These modalities act through overlapping neurobiological pathways that regulate arousal, circadian rhythms, and autonomic balance, positioning them as active modulators of sleep rather than passive background factors [19].

Light-based interventions provide a non-invasive and adjustable means of aligning the sleep-wake cycle with environmental cues [14], supporting circadian rhythm synchronization [16]. Accordingly, the European Insomnia Guideline recommends light therapy as adjunct cognitive behavioral therapy for insomnia (CBT-I) [17], though overall evidence remains mixed due to small, heterogeneous, and population-specific studies [18]. Auditory and thermal factors similarly influence sleep physiology: calming soundscapes can reduce autonomic arousal and mask disruptive noise that fragments sleep [19], while cooler ambient temperatures support thermoregulation and the core body temperature decline needed for sleep onset and deeper slow-wave sleep [20].

Across sensory modalities, current findings are encouraging but still limited in scope and consistency, underscoring the need for more rigorous, comparative studies. Nevertheless, sensory cues may also enhance the quality and continuity of sleep by deepening slow-wave activity, stabilizing rapid eye movement (REM) cycles, and improving overall efficiency [21]. Because disturbances in these processes contribute to fatigue, reduced cognitive performance, and increased risk for psychiatric [8], cardiovascular [9], metabolic [10], and immune disorders [22], integrating sensory-based strategies with established behavioral or pharmacologic therapies may provide synergistic benefits for sleep quality, adherence, and long-term outcomes. This narrative review highlights studies using light, sound, and temperature as therapeutic tools for improving sleep health and explored how integrating these modalities as adjunct to behavioral approaches may offer clinicians practical, low-risk strategies to improve sleep quality.

2. Light as a Therapeutic Tool

2.1. Mechanisms of Light on Sleep

Light is the primary zeitgeber (environmental cue) for circadian regulation, directly influencing melatonin secretion and phase timing according to its intensity, spectrum, and timing [23,24]. Controlled light exposure therefore offers a non-invasive way to realign the sleep-wake cycle with environmental cues. Ocular exposure to light directly influences the suprachiasmatic nucleus (SCN), the central pacemaker that regulates circadian timing and the sleep-wake cycle [25], through a specialized class of retinal neurons, even in individuals who are totally visually blind [26]. In general, morning exposure to bright light in the blue-enriched spectrum (**Supplemental Figure 1**) has been found to best advance circadian rhythms, suppressing melatonin secretion and promoting wakefulness, while evening exposure to blue-enriched light delays circadian phase and hinders sleep onset [23]. Clinical applications of light therapy typically employ bright light of 1000-10,000 lux for 20-30 minutes, with morning light most effective within 1-2 hours of waking, showing modest improvements in sleep latency and efficiency [27,28] (**Table 1, Supplemental Table 1**). However, the practical clinical translation of mechanistic light parameters remains limited by variation in study designs and mixed outcome findings [29,30].

Table 1. Light-Based Sleep Interventions Across Select Populations.

Population	Light Intervention	Reported Outcomes	Evidence Level	Reference
Infants / children	Controlled morning daylight, dim evening environment	Enhanced circadian consolidation, reduced sleep latency	Expert consensus/small observational studies	[52]
Typical adults	Morning bright-light exposure (>1000 lux); reduced evening light	Advanced circadian phase, improved sleep quality	Systematic review of mixed quality studies	[32]
Adults with insomnia / shift workers	Morning or shift-timed bright-light therapy	Advanced circadian phase, reduced fatigue	Systematic review and meta-analysis of RCTs	[30]
Neurodivergent populations (ASD/ADHD)	Timed bright-light exposure with sensory regulation	Reduced night awakenings, improved adaptability	Small pilot studies and case series	[35]
Older adults / neurodegenerative disease	Daylight or biologically directed bright-light therapy	Improved sleep efficiency, mood, and circadian stability	RCT and meta-analysis of RCTs	[64]

2.2. Clinical Applications Across Populations

2.2.1. Typical Adults

Even in healthy, community-dwelling adults, modern lifestyles often limit daytime light exposure and extend artificial light use into the evening. This mismatch between natural and artificial light-dark cycles can weaken circadian entrainment and reduce sleep quality [31]. A systematic review synthesizing 45 studies on the effects of light therapy in typical, community-dwelling adults found that bright light exposure of >1000 lux was generally associated with better objective and subjective sleep outcome measures than dim or moderate light [28]. Morning light exposure advanced circadian phase and improved self-reported sleep quality, whereas evening exposure delayed sleep onset and was linked to poorer sleep [28]. These findings align with experimental studies demonstrating that morning bright light therapy enhances sleep efficiency, stabilizes circadian timing, and promotes alertness during waking hours [32,33]. Conversely, reducing evening light exposure through dimming household lights 2-3 hours before bedtime or using blue-blocking glasses has been shown to support melatonin secretion and advance sleep onset [34,35]. Despite consistent findings, many studies rely on short-term interventions and self-reported outcomes. Future research should clarify optimal light intensity, duration, and timing for long-term circadian alignment across diverse real-world environments.

2.2.2. Sleep Disorders

Individuals with sleep disorders often experience disrupted circadian rhythms and impaired light responsiveness, which can weaken the natural alignment between internal biological timing and

environmental light-dark cycles. This dysregulation contributes to difficulties with sleep initiation, consolidation, and daytime alertness [36]. Light therapy has been widely studied in sleep disorders, where structured bright-light exposure appears to support circadian regulation, improving sleep initiation, consolidation, and daytime alertness, though effect sizes and outcomes vary. For sleep disorders caused by extrinsic factors such as shift works, a systematic review found that light therapy was associated with improvements in sleep efficiency, reduced insomnia severity, and enhanced daytime alertness among shift workers [30]. These extrinsic sleep disorders benefit from strategic timed light exposure before or during night shifts and light avoidance post-shift, rather than fixed scheduling, which facilitates circadian adaptation and minimizes fatigue [37]. Bright light therapy is also found to complement pharmacologic or device-based interventions for intrinsic sleep disorders such as such as insomnia and circadian rhythm sleep-wake disorders [23]. A recent meta-analysis of 13 randomized controlled trials in adults with insomnia found that light therapy reduced wake after sleep onset, although it did not reliably improve sleep latency, total sleep time, or sleep efficiency [29]. The American Academy of Sleep Medicine guideline endorsed appropriately timed light therapy for intrinsic circadian rhythm disorders though noted evidence quality remains low [18]. For these conditions, structured bright light therapy (typically morning exposure exceeding 2,500 lux for 30–60 minutes) can help advance or stabilize circadian phase and reinforce sleep-wake regularity [23]. Moreover, in hypersomnolence disorders like sleep apnea and narcolepsy, light therapy may serve as a complementary intervention to pharmacologic or device-based treatments, helping alleviate residual daytime sleepiness and enhance alertness [38,39]. For instance, an open-label trial (n=30) of morning bright light therapy found significant improvements sleepiness and sleep quality after 4 weeks [38]. Larger randomized controlled trials with sham-light controls are needed to establish efficacy and optimal treatment parameters for this population. Finally, preliminary studies suggest a role for light in modulating REM sleep timing, reducing the frequency of parasomnias, which refer to abnormal sleep behaviors such as sleepwalking, night terrors, or REM sleep behavior disorder, and mitigating restless legs syndrome by influencing dopaminergic tone [40–42]. Further research is needed to clarify these mechanisms and establish clinical relevance.

2.2.3. Mood Disorders

Individuals with mood disorders often experience disrupted circadian rhythms and abnormal light sensitivity, which can contribute to sleep-wake irregularities and mood instability. These disturbances may exacerbate depressive symptoms and reduce treatment responsiveness [43]. Light therapy has been shown to offer antidepressant effects in mood disorders. In a systematic review analyzing 15 randomized controlled trials, bright light therapy significantly decreased depressive symptoms in patients with major depressive disorder, and was associated with a higher response rate to psychotherapy and pharmacotherapy at the end of the trial, compared to placebo [44]. Similarly, positive outcomes have been reported in nonseasonal depressive disorders, where bright light served as an effective adjunct treatment to antidepressants and may improve the response time to the initial treatment [45]. For seasonal affective disorder, bright light therapy improved fatigue, excessive daytime sleepiness, and health-related quality of life, and is widely considered a first-line intervention [27,46]. Moreover, bright light exposure also produced significant mood stabilization in both bipolar and unipolar depression [47,48]. Recent research in schizophrenia also demonstrated that light exposure improved psychiatric scoring and cognitive performance, potentially complementing pharmacologic therapy by mitigating circadian misalignment and enhancing sleep-wake consistency [49]. These findings suggest that bright light therapy is a well-tolerated, evidence-based intervention that can enhance mood, stabilize circadian rhythms, and serve as an effective adjunct to pharmacologic and psychotherapeutic treatments across multiple psychiatric conditions. For clinical application, bright light therapy delivered via 10,000-lux light boxes for 30–45 minutes each morning can be used as monotherapy for seasonal affective disorder and as an adjunct to antidepressant or mood-stabilizing treatment in nonseasonal and bipolar depression [27,50]. For patients with schizophrenia or mood instability, structured morning light exposure combined with

evening light restriction may help stabilize circadian rhythm and augment pharmacologic efficacy[49]. While efficacy is well established, further studies are needed to define optimal timing, duration, and wavelength parameters for nonseasonal and bipolar depression. Longitudinal and mechanistic studies are also required to clarify how light influences neurotransmitter systems and cognitive outcomes in severe mood and psychotic disorders.

2.2.4. Neurodivergent Populations

Individuals with neurodevelopmental conditions such as autism spectrum disorder (ASD) and attention-deficit/hyperactivity disorder (ADHD) frequently experience disrupted sleep-wake regulation. Factors such as sensory hypersensitivity, irregular light exposure, and difficulties with bedtime transitions can compound circadian misalignment and sleep disturbance [51]. Emerging research indicates that structured morning or daytime light exposure, paired with reduced evening light, can improve sleep initiation, reduce nighttime awakenings, and enhance daytime behavior for these neurodivergent populations when integrated into individualized, sensory-based care plans [52]. Recent studies highlight the importance of timing, intensity (lux), and wavelength (blue vs. red light) of light exposure in affecting sleep quality [35,53], and that pairing light exposure with other sensory strategies (massage, compression garments) and predictable pre-sleep routines enhances consistency and generalization across settings [54]. For neurodivergent individuals, light-based interventions are considered to be personalized to sensory tolerance and daily structure, such as scheduling morning light exposure within one hour of waking, maximizing natural daylight during the day, and using low-intensity, warm lighting in the evening [51]. Incorporating these light routines into multimodal sensory programs, along with occupational therapy, relaxation techniques, and structured bedtime rituals, is associated with more stable sleep patterns and daytime regulation [52]. However, existing studies are limited by small sample sizes, heterogeneous methodologies, and variable outcome measures. Larger controlled trials are needed to determine optimal light parameters and to clarify whether effects differ by diagnosis, age, or sensory profile. Longitudinal research is also warranted to explore how early light-based interventions may influence developmental trajectories in sleep and emotional regulation.

2.2.5. Pain Management

Pain and sleep are bidirectionally linked, with disrupted sleep increasing pain sensitivity and persistent pain impairing sleep initiation and maintenance. This cycle of hyperarousal and poor sleep can worsen fatigue, emotional distress, and overall quality of life [55,56]. Daytime bright-light exposure and evening dim light has been shown to lower hyperarousal and improve sleep continuity, while reducing chronic pain intensity and improving depressive symptoms in adults with chronic back pain [57,58]. For example, in a randomized 4-week trial involving individuals with fibromyalgia, one hour of daily morning light (both bright and dim conditions) led to improvements in pain intensity, pain interference, physical function, depressive symptoms, and sleep disturbance [59]. Similarly, among individuals with cancer who often experience disturbed sleep due to pain and fatigue [60], a recent meta-analysis (N= ~700) found that bright light therapy improved sleep quality, total sleep time, wake after sleep onset, and reduced fatigue, suggesting bright light therapy as a supplementary option for improving sleep continuity and reducing fatigue [61]. Thus, incorporating light therapy into multimodal pain management may help normalize circadian rhythm and attenuate pain perception. Morning bright-light exposure ($\geq 2,500$ lux for 30–60 minutes) and evening light reduction can support sleep restoration and mood regulation for pain management [62]. Light therapy may also complement behavioral or pharmacologic pain interventions by improving alertness and reducing depressive symptoms associated with chronic pain [58,62]. Although initial findings are promising, studies vary widely in sample size, light intensity, and timing protocols. Further randomized controlled trials are needed to determine optimal parameters and to clarify whether light's analgesic effects are mediated primarily through sleep improvement, circadian alignment, or direct modulation of pain-processing pathways.

2.2.6. Aging and Neurodegenerative Diseases

As circadian rhythm weakens with age, individuals often experience fragmented sleep, daytime sleepiness, and agitation [63]. Structured light interventions show promise for improving sleep disturbances common in aging and neurodegenerative conditions such as Parkinson's disease (PD), Alzheimer's disease (AD), and other forms of dementia. A randomized controlled trial demonstrated that biologically directed daylight therapy improved sleep, mood, and circadian stability in individuals with PD [64]. Similarly, in individuals with AD, light therapy improved sleep and psychobehavioral symptoms, as well as reduced depression and agitation, reinforcing its role in dementia care [65]. Consistent with these findings, a meta-analysis of randomized controlled trials including over 1000 individuals with clinical dementia reported that light therapy was associated with improvements in overall sleep quality (increased total sleep time and efficiency and fewer awakenings), while also decreasing depression and neuropsychiatric symptoms and improving cognitive function [66]. These findings highlight that light therapy can serve as a low-risk, circadian-focused intervention that can stabilize rest-activity patterns and improve behavioral symptoms in older adults and those with neurodegenerative disease. Implementing consistent daytime light exposure and morning bright light schedules in residential or care settings may further improve patient outcomes reduce caregiver burden by promoting regular sleep-wake cycles and limiting evening agitation [67]. Despite growing evidence, heterogeneity in light protocols (intensity, duration, and spectral composition) and variations in disease stage limit generalizability. Future research should aim to define standardized intervention parameters and investigate whether tailored light exposure can slow cognitive decline or neurodegenerative progression.

3. Auditory Interventions for Sleep

3.1. Mechanisms of Common Sound Types on Sleep

The human auditory system remains active during sleep [68]. While this adaptation serves the evolutionary purpose to detect potential threats in the surrounding environment, it can also interfere with sleep. Controlled and predictable auditory stimulation has been demonstrated to aid sleep initiation and maintenance by masking disturbing environmental noises, promoting relaxation, and functioning as a cue for sleep for stimulus control [68]. When applied strategically, these soundscapes can be utilized therapeutically to improve sleep quality. Common sound types for auditory sleep intervention include white, pink, and brown noises (**Table 2, Supplemental Figure 2**), indicating different audio frequencies in analogy to the color spectrum of light. Briefly, white noise distributes equal intensity across all audible frequencies (~20 Hz to 20,000 Hz), creating balanced sound often perceived as "humming" or "hissing" [68]. Pink noise emphasizes lower frequencies, providing a deeper characteristic resembling ocean waves [68]. Brown noise further emphasizes lower frequencies, creating a deep rumbling sound [68]. For therapeutic applications, sound interventions are typically delivered at 30-80 dB, to mask environmental noise without causing auditory overstimulation [19]. A systematic review found that masking and relaxation are the primary pathways, though effects on sleep continuity are variable across protocols [19]. Continuous delivery throughout the night or timed cessation after sleep onset both show effects, with selection depending on individual preference and environmental noise patterns [19,69]. Other sounds include autonomous sensory meridian response (ASMR), which is often described as a tingling sensation triggered by specific visual-auditory stimuli [70], natural soundscapes such as birdsong, wind, or trembling leaves [71], as well as music therapy including listening to music, playing musical instruments, or singing [71]. A systematic review on the effects of sound and music interventions for individuals in an intensive care unit (ICU) from 59 independent studies revealed that white, pink, brown noises improved sleep quality and reduced pain in standardized questionnaires, while natural sounds reduced anxiety and agitation levels in standardized assessments, with improved hemodynamic measurements such as reduced blood pressure, slowed respiratory and heart rates, and increased oxygen saturation via vital sign monitoring, all aligning with a deeper relaxation state

[72]. Additionally, music therapy was also found to improve sleep quality, decrease anxiety, and reduce pain in standardized questionnaires, along with improved hemodynamic measurements and reduced stress-related biomarker secretions such as blood and urinary cortisol, MET-enkephalin (an endogenous opioid peptide involved in pain relief and stress modulation), and blood prolactin (a pituitary hormone that influences immune function, metabolism, and stress responses) [72]. Closed-loop auditory stimulation that phase-locks tones to slow oscillations can acutely enhance slow-wave activity, including in older adults at home [73] (Table 2, Supplemental Table 2). However, findings across studies remain heterogeneous: while some report improvements, others show minimal or no effects. Two recent reviews conclude that benefits of continuous broadband noise (e.g., white/pink/brown) are mixed and population-dependent[19]. The World Health Organization recommends bedroom sound levels <30 dB LAeq at night and limiting single events to <45 dB Lmax to minimize sleep disturbance [74], although therapeutic soundscapes are often used above these thresholds for masking and should be individualized [68]. An environmental-noise update likewise emphasizes adverse sleep effects above these ranges [69].

Table 2. Common Sound Interventions and Sleep Outcomes.

Sound Type	Description	Sleep-Related Effect	Population / Context	Reference
White noise	Equal intensity across all frequencies	Masks environmental noise, reduces nighttime awakenings	School-aged children with poor sleep hygiene	[157]
Pink noise	Emphasis on lower frequencies	Promotes slow-wave sleep and improves memory consolidation	Older adults and individuals with mild insomnia	[73]
Brown noise	Deep, low-frequency emphasis	Calms hyper-responsivity, supports relaxation	Adults with sensory over-responsivity or anxiety-related insomnia	[158]
Nature sounds	Water, wind, or forest ambient sounds	Induces relaxation and decreases sleep latency	Preschoolers with ASD; adults with stress-related insomnia	[159,160]
ASMR (audio-sensory response)	Soft whispering, tapping, rhythmic audio cues	Triggers tingling relaxation response, decreases heart rate, improves subjective sleep onset	Young adults with sleep onset difficulties	[161]
Music therapy	Calm instrumental or slow-tempo rhythmic patterns (≤ 60 bpm)	Reduces sleep onset latency, enhances perceived sleep quality	Older adults and individuals with insomnia symptoms	[88]

3.2. Clinical Applications and Populations

3.2.1. Typical Adults

Even healthy adults are increasingly exposed to environmental and psychological stressors, such as digital stimulation, noise pollution, and irregular routines, that elevate pre-sleep arousal and disrupt the transition from wakefulness to rest [75]. Auditory interventions have emerged as effective, non-invasive strategies to promote sleep quality in healthy adults. Calming soundscapes, slow-tempo music, and pink or brown noise have been shown to reduce pre-sleep arousal, stabilize heart rate and breathing, and facilitate the transition from wakefulness to NREM sleep [19]. Using sounds synchronized to slow oscillations, termed “rhythmic auditory stimulation”, can further enhance slow-wave activity, deepening restorative sleep and improving next-day alertness and memory performance [76]. Moreover, music with low-frequency, steady rhythms (60–80 bpm) can entrain relaxation by aligning with resting heart rate patterns and decreasing sympathetic nervous system activity [19]. These findings suggest that for typical adults, structured use of auditory intervention before and during sleep may serve as an accessible sleep hygiene tool that not only promote relaxation but also directly modulate neural synchronization and autonomic balance, offering a simple yet biologically grounded approach to optimizing sleep in healthy individuals. Recommended practices include 20–45 minutes of calming, rhythmic music at low volume before bedtime, or continuous playback of pink or brown noise to mask environmental sounds [48]. Integration with relaxation or mindfulness routines may further enhance autonomic downregulation and consistency of benefits [77]. Despite promising effects, studies vary in sound type, delivery method, and participant age, limiting generalizability. Further controlled trials are needed to define optimal sound characteristics, exposure timing, and long-term effects on sleep architecture and cognitive outcomes.

3.2.2. Intensive Care Units (ICUs) Environment

Individuals in ICUs experience continuous exposure to environmental noise from medical equipment, alarms, and staff activity, which interrupts sleep architecture, increases arousal frequency, and elevates the risk of pain sensitization and delirium [78]. Recent studies reported that carefully designed auditory interventions mitigated these risks and enhance sleep quality [79]. A component network meta-analysis supports the effectiveness of sound and darkness interventions for improving sleep outcomes in critically ill adults [79]. Likewise, evidence-based sound interventions were found to be more effective in achieving objective and patient-reported sleep outcomes in a prospective, single-blind, clustered control trial on patients in awake ICUs [80]. Moreover, combining music therapy with light reduction through eye masks enhanced sleep quality and lowered delirium incidence in postoperative ICU patients in a randomized controlled trial, supporting the value of a multimodal sensory approach in pain management and critical care [81]. These results align with broader ICU reviews highlighting noise-related sleep disruption and the value of soundscapes as part of bundled care. When combined with light management (e.g., dimming lights or using eye masks), these multimodal sensory approaches may further reduce delirium risk, pain perception, and physiological arousal in critically ill patients [82]. Despite promising findings, variability in intervention type, duration, and patient condition limits standardization across ICU settings. Future research should clarify optimal sound parameters (volume, frequency range, exposure timing) and evaluate combined sensory protocols for long-term recovery, neurocognitive outcomes, and staff implementation feasibility.

3.2.3. Neurodivergent Populations

Individuals with neurodevelopmental conditions such as ASD often exhibit heightened sensory sensitivity and difficulty regulating arousal, contributing to delayed sleep onset, frequent nocturnal awakenings, and irregular circadian rhythms [52]. Auditory interventions serve as valuable regulatory tools for achieving both sleep initiation and maintenance in neurodivergent populations [83]. Emerging clinical reports suggest that white noise can reduce sleep latency and nocturnal awakenings in children with ASD, though study sizes remain small [84]. Another recent systematic review and meta-analysis indicates that acoustic stimulation (including white/pink noise) can

enhance sleep efficiency and continuity in insomnia, with applicability across neurodivergent and neurotypical groups, while emphasizing protocol standardization needs [85]. When incorporated into structured bedtime routines, auditory stimulation strategies have also been found to reduce nocturnal awakenings and promote circadian stability across diverse patient groups [19]. Implementation typically involves a trial period where caregivers introduce 3-4 different sound types at low volume, allowing the patient to select the most tolerable option. Once selected, maintaining consistency with the same sound nightly supports stimulus control associations and reduces bedtime resistance [86]. Current evidence is limited by small sample sizes, heterogeneous sound types, and lack of standardized exposure protocols. Future research should explore long-term outcomes, determine optimal frequency and duration parameters, and clarify how sensory integration principles can inform auditory intervention design across diverse neurodivergent profiles.

3.2.4. Aging and Neurodegenerative Diseases

Aging and neurodegenerative conditions such as AD and PD are frequently accompanied by circadian dysregulation, fragmented sleep, and nighttime agitation. Cognitive decline, altered sensory processing, and neurochemical changes (including dopaminergic deficits) further compound difficulties in maintaining restorative sleep [87]. Music therapy has been increasingly recognized as a therapeutic intervention to reduce agitation, improve cognition, and stabilize sleep patterns in aging and neurodegenerative populations [88]. Meta-analyses in older adults suggest small-to-moderate improvements in subjective sleep quality with music listening, with heterogeneity across trials [89,90]. A systematic review of randomized controlled trials found that music therapy in individuals with AD not only improved cognitive function but also enhanced sleep regulation and reduced nighttime restlessness [91]. For individuals with PD, rhythmic auditory stimulation has been associated with improved motor coordination and sleep quality by modulating dopaminergic and circadian pathways [76]. These findings align with broader evidence that auditory interventions help improve sleep continuity and mood while reducing caregiver burden in dementia care homes [92]. Similarly, slow-wave auditory stimulation and pink-noise approaches can augment slow-wave activity and, in some trials, memory consolidation in older adults [73,93]. Collectively, these findings support auditory stimulation as a versatile, non-pharmacological intervention for improving sleep and overall quality of life in senior adults with neurodegenerative diseases or dementia. Practical approaches include evening music therapy sessions with calming, familiar melodies to reduce agitation, or rhythmic auditory stimulation to improve motor and circadian regulation. In institutional care, incorporating consistent background soundscapes or gentle pink-noise playback can promote relaxation and minimize nighttime disturbances [19]. Despite encouraging results, heterogeneity in intervention design, such as music type, tempo, and delivery method, limits reproducibility. Future trials should standardize sound exposure parameters, assess long-term effects on cognitive and sleep outcomes, and explore underlying neural mechanisms linking auditory entrainment to circadian and dopaminergic modulation.

4. Thermoregulation for Sleep

4.1. Mechanism of Cooling on Sleep

Core body temperature naturally decreases during sleep due to reduced muscle tone and metabolic heat production [94]. Cooling before or during sleep facilitates this physiological decline (**Supplemental Figure 3**), leading to reduced sympathetic tone and enhanced parasympathetic activity [95]. These autonomic shifts facilitate quicker sleep onset and more restorative, deeper NREM sleep stages [94]. Optimal ambient temperature varies by age and context; typically ranging from 19-21°C for many adults and 20-25°C for older adults, with humidity and bedding influencing perceived comfort [20,96,97]. In a study of cold-water immersion over the course of 4 weeks, pre-sleep cooling showed benefits such as improved sleep quality, cognitive performance, and well-being [98]. Other body cooling strategies can be achieved through environmental temperature control, choice of

sleepwear/bedding fibers, or active cooling devices including cooling mattress pads or toppers for individuals with specific needs such as vasomotor symptoms [99]. Studies have shown that cooling bedding materials reduced sleep disturbance and improved sleep efficiency in peri- or post-menopausal women with vasomotor symptoms of hot flashes and night sweats [100,101], women receiving endocrine therapy for breast cancer experiencing similar symptoms [102], or healthy men [103]. In addition, a randomized, sham-controlled trial of a forehead temperature-regulating device (two treatment nights) improved several polysomnographic latency measures [104]. Together, these results indicate that cooling strategies represent a safe, non-pharmacological approach to support vagal activity and improve sleep quality (**Table 3**). Although cooling-based interventions have shown promise, the evidence base remains limited. Trials are generally small and short in duration, with heterogeneous outcome measures and limited independent replication [104–106]. Further research using standardized sleep metrics and long-term follow-up is needed to establish their clinical utility.

Table 3. Thermal Environment Interventions and Reported Outcomes.

Intervention	Reported Effect	Population	Reference
Warm bath before bedtime	Improved sleep onset and efficiency through thermoregulation	Healthy adults	[162]
Cooling the sleep environment	Reduced nighttime awakenings, improved sleep satisfaction	Menopausal women	[107]
Temperature-controlled bedding	Enhanced sleep continuity, decreased awakenings	Healthy adults	[105]
Gentle thermal gradients (fan + ambient cooling)	Improved alertness, reduced sleep inertia	Shift workers	[126]

4.2. Clinical Applications and Populations

4.2.1. Menopausal Women

During menopause, fluctuations in estrogen and progesterone disrupt thermoregulation, leading to vasomotor symptoms such as hot flashes and night sweats. These episodes often occur at night, fragmenting sleep and reducing overall sleep efficiency and restorative rest [107]. Targeted thermoregulation strategies have demonstrated clinically meaningful benefits in improving rest in menopausal women who experience vasomotor symptoms [107]. Preliminary clinical studies – ranging from a pilot trial of a cooling mattress pad to a randomized trial of a cool-pad pillow topper in women on endocrine therapy – report reductions in vasomotor symptoms and sleep disturbance, highlighting the value of peripheral cooling in mitigating nocturnal awakenings [100,102]. A novel wrist-cooling device was also found to support management of vasomotor symptoms in both cancer treatment-induced and natural menopause, improving sleep continuity by attenuating thermoregulatory stress [76,108]. These peripheral cooling interventions are most effective initiated before bedtime and maintained overnight to stabilize core body temperature [79,86]. For optimal results, individual comfort and symptom timing may be considered. Integration of these strategies with other behavioral measures, such as maintaining a cool bedroom environment and wearing breathable fabrics, can further support uninterrupted sleep [109]. Although early trials show promise, studies remain limited by small sample sizes and variable device types. Larger randomized controlled studies are needed to determine optimal cooling parameters, assess long-term adherence, and evaluate the comparative effectiveness of localized versus whole-body thermal regulation.

4.2.2. Other Adults

For adults across broader populations, including men, younger women, and older adults, temperature-controlled environments consistently influence sleep quality and physiological recovery. Environmental overheating, metabolic differences, or inadequate thermal environments can delay sleep onset, fragment sleep, and impair physiological recovery [20]. Studies have shown that maintaining ambient bedroom temperatures between 20–25°C supports melatonin release and reduces nighttime awakenings across age and sex groups [20]. One week of sleeping on a temperature-controlled mattress cover improved sleep stages and cardiovascular recovery, suggesting systemic benefits beyond subjective rest [105]. Similarly, a pilot study found that cooling bed sheets improved sleep among individuals who described themselves as “hot sleepers,” providing practical support for bedding innovations as sleep-enhancing tools [110]. Furthermore, a systematic review found that physiologic cooling facilitated by bedding showed mixed but promising effects on sleep outcomes and noted the need for standardized protocols [111]. For individuals prone to overheating, temperature-controlled bedding, breathable fabrics, and adjustable cooling systems can further enhance sleep continuity and next-day alertness [105]. Integrating personalized cooling tools into general sleep hygiene routines may improve both comfort and circadian alignment [20]. Although findings consistently link thermal environment to sleep quality, research remains limited by short intervention durations and varied methodologies. Future studies should investigate optimal cooling gradients, the interaction of ambient versus surface temperature, and long-term physiological outcomes such as recovery metrics and metabolic health.

4.2.3. Veterans

Veterans are at heightened risk for chronic sleep disturbance due to persistent hyperarousal, disrupted circadian rhythms, and impaired thermoregulation arising from trauma exposure and chronic stress. These physiological and psychological factors often sustain insomnia, nightmares, and fragmented sleep despite behavioral or pharmacologic interventions [112]. Augmenting conductive heat loss during sleep has been linked with increased slow-wave sleep and calmer cardiac autonomic profiles [113] and cooling strategies help promote parasympathetic activity and reduce core body temperature, facilitating the transition into restorative sleep [20]. A 4-week pilot study of a forehead cooling device in veterans with chronic insomnia showed significant improvements in insomnia severity and mood symptoms [114], supporting temperature-based therapies as a promising, low-risk adjunct for improving sleep and emotional regulation in veterans coping with trauma-related sleep disturbances. Targeted cooling interventions, such as forehead or wearable cooling devices, may be considered to be incorporated into bedtime routines to counteract hyperarousal and promote relaxation. Maintaining a slightly cooler bedroom environment (18–22 °C) and employing conductive cooling materials (e.g., gel pads, cooling fabrics) may further enhance thermoregulatory downshifting [115]. When integrated with trauma-informed behavioral therapies, these methods may complement sleep hygiene practices and pharmacologic treatment. Existing studies are preliminary, with limited sample sizes and heterogeneous designs. Larger randomized controlled trials are needed to confirm efficacy, establish optimal cooling parameters, and explore whether temperature regulation directly modulates autonomic reactivity or indirectly benefits sleep through stress reduction.

5. Sensory Profile Assessment and Individualization

Individuals differ widely in how they process sensory input related to sleep. A sound, light, or temperature change that is calming for one person can provoke hyperarousal in another, reflecting stable differences in sensory thresholds and regulation. These differences help explain why standardized sleep-hygiene recommendations often yield inconsistent results. Assessing these patterns (referred to as “sensory profiling”) can guide individualized adjustments to sensory environments and improve adherence.

In clinical practice, sensory profiling can be introduced when sleep difficulties coexist with sensory sensitivities, neurodevelopmental conditions, or poor response to standard CBT-I approaches [116,117]. A stepped approach begins with brief screening about environmental preferences, including preferred room temperature, tolerance for background sounds, and sensitivity to light, which can guide initial intervention selection [118], which takes approximately 5-10 minutes during intake and helps identify patients who may benefit from formal sensory profiling. For patients requiring more detailed assessment, validated instruments include the Adolescent/Adult Sensory Profile (AASP) for individuals aged 11 years and older provides standardized scores across four sensory processing patterns [119,120]. The assessment generates a profile indicating whether an individual demonstrates low registration (missing sensory cues), sensory seeking (craving intense input), sensory sensitivity (detecting stimuli others miss), or sensation avoiding (actively limiting exposure) [119,121]. These patterns reflect underlying differences in neurological thresholds that inform how much intensity or predictability of sensory cues a person tolerates to guide intervention selection [119]. For example, individuals with sensory sensitivity or sensation avoiding patterns may require gentler sensory inputs, such as predictable dim evening light (< 30 lux) [122], soft pink or brown noise (~ 35-65 dB) [123], and moderate nighttime cooling (17-20 °C) to prevent hyperarousal [124]. Conversely, individuals with low registration or sensory seeking patterns may benefit from stronger cues such as bright morning light (2,000–10,000 lux) [28], white noise with greater amplitude [125], and larger temperature contrasts (2-3 °C) [97] to effectively signal sleep-wake transitions. Recent RCTs in shift workers demonstrated increased total sleep time by roughly 30 minutes and improved efficiency when light exposure was individualized [33,126]. Similarly, research on auditory processing during sleep revealed that identical noise stimuli can stabilize or fragment sleep depending on cortical K-complex reactivity [127,128]. Systematic reviews in ASD also show that tailoring environmental stimuli to sensory profiles reduces bedtime resistance and improves sleep initiation [129,130]. Incorporating sensory preferences into intervention design has also improved sleep quality and caregiver satisfaction [130,131]. These findings highlight substantial variability between individual responses to sensory interventions, and that personalization in clinical applications is critical to maximize sleep benefits to individual patients.

However, the evidence base for sensory profile-guided intervention selection remains preliminary. Most studies of light, sound, and temperature interventions have not systematically assessed baseline sensory processing characteristics or analyzed outcomes stratified by sensory profile. Prospective studies are needed that: (1) apply sensory assessment tools before intervention selection; (2) test whether matching interventions to sensory profiles improves outcomes compared to non-tailored approaches; and (3) identify which sensory patterns predict differential treatment responses. Such research would establish whether formal sensory profiling adds clinical value beyond standard CBT-I assessment and informal preference screening. Future research should prospectively apply sensory assessment tools to guide intervention selection and test differential treatment responses across sensory patterns, thereby building the evidence base for precision sensory-based sleep care.

6. Multisensory Integration

Although light, sound, and temperature act through different senses, they influence common biological systems that regulate sleep. Each can help synchronize circadian rhythms, lower physiological arousal, and promote parasympathetic activity to support the body's natural transition to rest [132]. Emerging evidence suggests that combining sensory modalities (i.e., combining two or more sensory-interventions simultaneously or sequentially) may produce synergistic rather than additive effects on sleep outcomes [133,134]. When multiple sensory cues are aligned in timing and direction such as dimming light while lowering temperature and reducing noise, the resulting neural signal can be stronger than the sum of its individual effects, a phenomenon known as super-additive multisensory integration [135]. The neurobiological basis for the synergistic effects may involve convergent modulation of arousal systems, where simultaneous targeting of visual, auditory, and

thermosensory pathways produces more robust suppression of sympathetic tone and enhancement of parasympathetic activation than single-modality approaches [136]. This, in turn, stabilizes cardiovascular variability [137] and attenuates hypothalamic–pituitary–adrenal (HPA) axis activation [138], promoting deeper non-REM sleep and improved recovery [139]. Functional imaging further shows overlapping activation in preoptic and brainstem nuclei during coordinated sensory relaxation stimuli [140,141], reinforcing a shared physiological substrate that supports cross-modal sensory integration. From a practical standpoint, coordinating multiple sensory inputs through user-friendly delivery systems may improve compliance compared to managing separate interventions, though this requires devices that maintain simplicity while avoiding over-complexity that could reduce adherence.

In clinical contexts, multisensory approaches show increasing promise. For example, a study demonstrated that multisensory stimulation combining sound, aromatherapy, and temperature adjustments significantly improved relaxation and sleep quality in rotating shift workers, reducing cortisol and shortening sleep-onset latency more effectively than sound alone [92]. Similarly, a bedroom-based multisensory intervention that simultaneously manipulated light spectrum, ambient sound, and temperature reduced sleep inertia and improved Psychomotor Vigilance Test performance and subjective alertness compared with unimodal controls [142]. In critical care settings, combining music therapy with light reduction via eye masks improved sleep efficiency and reduced delirium incidence relative to single-modality interventions [81]. Finally, other sensory modalities such as tactile stimulation (weighted blankets) and olfactory inputs (aromatherapy) have been explored for improving sleep [143–145], although light, sound, and temperature remain the most evidence-supported domains.

Despite encouraging findings, rigorous trials directly comparing multisensory versus unisensory interventions, using factorial or crossover designs to test main effects vs. interactions between modalities, and measuring adherence, dose, and timing of intervention components, remain limited. Commercial multimodal devices are beginning to emerge in the consumer market, but these lack large-scale validation studies comparing their effectiveness to established single-modality interventions or to combined CBT-I approaches. Future research is needed to test combinations of light, sound, and temperature with objective autonomic and behavioral outcomes. Identifying optimal timing, sensory congruence, and population-specific tailoring (e.g., shift workers, individuals with neurodevelopmental conditions, ICU patients) will help clarify how cross-modal integration can be systematically harnessed to enhance sleep health and recovery. Importantly, studies should evaluate whether multimodal devices succeed where sequential introduction of single modalities has shown limited adherence, as the convenience of integrated systems may improve real-world implementation despite requiring further evidence for clinical efficacy.

Together, these sensory modalities influence complementary components of the sleep-regulatory system, where light modulates circadian phase and melatonin secretion, sound shapes autonomic and arousal states, and temperature regulates homeostatic thermoregulatory drive. When delivered in concert, these cues can synchronize circadian, autonomic, and homeostatic processes, producing faster sleep onset, deeper slow-wave sleep, and improved continuity. This convergence provides the biological rationale for multisensory packages that combine light, sound, and temperature adjustments to reinforce each other's effects.

7. Clinical Integration with CBT-I

Cognitive Behavioral Therapy for Insomnia is the first-line, evidence-based non-pharmacological treatment for chronic insomnia lasting more than 3 months [11]. It addresses maladaptive stress responses by reorganizing behavioral and cognitive patterns related to sleep [146,147]. Its core components – stimulus control, sleep restriction, cognitive restructuring, and relaxation training [147] – aim to rebuild healthy sleep associations with sleep and enhance overall sleep quality. In a recent meta-analysis of 241 RCTs including >30,000 participants, these core elements of CBT-I improved subjective sleep quality, sleep efficiency, sleep latency, wake after sleep

onset, and enhanced long-term remission rates of chronic insomnia [147]. Although CBT-I is widely regarded as the gold standard, first-line therapy, its therapeutic benefits can be limited in patients with comorbid conditions such as depression, chronic pain, ADHD, ASD, or sensory hypersensitivities, or where there are strong environmental contributors [146]. In such cases, integrating CBT-I with sensory-based interventions may prove more effective, as the use of light, sound, and temperature can provide external cues that reinforce therapy goals and improve adherence. This section discusses the integration of sensory-based strategies with CBT-I through three domains: stimulus and behavioral conditioning, cognitive restructuring, and relaxation-based interventions.

7.1. Sensory Support for Stimulus Control and Sleep Restriction

Stimulus control is a core foundation of CBT-I that works towards reconditioning the bedroom environment to signal sleep rather than wakefulness, and is associated with improved subjective sleep quality, sleep efficiency, and sleep latency [147]. Traditional approaches include restricting bed activities to sleep and sex, leaving bed when unable to sleep, and maintaining a consistent bedtime routine. Evidence suggests that sensory-based interventions can be integrated into these practices by providing consistent external cues that reinforce the desired sleep-wake relationship. For example, dimming evening light or using blue-blocking glasses [34,148], or introducing a regular bedtime soundscape have improved sleep outcomes [48,148,149]. These signals may be particularly helpful for individuals with insomnia or circadian rhythm disorders [148].

Sleep restriction is another key element of CBT-I, which aims to limit the time spent in bed to improve sleep efficiency. However, studies have shown negative effects associated with sleep-restriction therapy, such as exhaustion and reduced motivation [150], as many patients may experience difficulties in adherence. Integrating sensory-based interventions can help mitigate these effects and improve adherence and outcomes. For instance, external body cooling interventions, such as cooling mattresses, have been shown to increase slow-wave (NREM) sleep and lower heart rate [113], indicating parasympathetic activation and relaxation. Auditory interventions, including ASMR, have also been shown to reduce stress and anxiety while supporting relaxation and sleep, with medial prefrontal cortex activation observed in an fMRI study [151]. Therefore, sensory-based strategies can be integrated into stimulus control and sleep restriction strategies, serving as consistent external anchors for behavioral conditioning and improving adherence and lowering dropout rates. Because sleep concerns such as bedtime resistance, sleep anxiety, and delayed sleep onset are especially prevalent in autistic individuals [130], this combined approach may be particularly useful for those with sensory hyper-responsivity, such as children with ASD or adults with sensory processing differences, to ensure environmental consistency and compliance.

7.2. Sensory Reassurance for Cognitive Restructuring and Sleep Hygiene

Cognitive restructuring is another primary component of CBT-I that addresses maladaptive and dysfunctional thoughts about sleep, such as catastrophizing over not sleeping, which often perpetuate insomnia and contribute to pre-sleep arousal [11]. It promotes healthier thinking by examining these thoughts for accuracy and modifying them to be more rational [11]. Sensory interventions may support this process by providing concrete, non-pharmacological strategies that contribute positively to sleep. For example, an RCT combining bright light therapy with CBT-I and sleep education improved insomnia and sleep hygiene in adolescent patients with delayed sleep phase disorder (DSPD), showing reduced sleep latency, earlier sleep onset and rise times, increased total sleep time, and decreased wake after sleep onset, sleepiness, and fatigue [152]. Practical implementation involves scheduling light exposure at consistent times coordinated with sleep education sessions, typically 30-60 minutes of morning bright light within the first two hours of waking, paired with evening light reduction strategies [94,101]. These adjunct approaches not only support treatment adherence but may also improve sleep hygiene by reducing reliance on maladaptive coping strategies such as alcohol or cannabis use [146]. By tailoring sensory plans to

emphasize controllable elements and reduce focus on uncontrollable ones, cognitive restructuring enhances patients' ability to improve their sleep hygiene and optimize treatment outcomes.

7.3. Sequential Sensory Cues for Relaxation Training

Relaxation training is the final element of CBT-I, designed to reduce physiological arousal and promote parasympathetic nervous system activation before and during sleep [153,154]. Sensory approaches align conceptually with relaxation training goals by providing direct physiological pathways to relaxation, such as maintaining a cool bedroom climate, using forehead or mattress cooling, or engaging in brief cold water immersion [95,155], to reduce stress and induce calm prior to sleep. Similarly, predictable auditory inputs, such as white noise, pink noise, ASMR, natural sounds, and music, have been shown to support parasympathetic activation and decrease sleep latency and nocturnal arousal [48]. These relaxation techniques may be especially effective at reducing sleep onset latency for patients with chronic pain [113,154]. Sensory-based relaxation can be introduced progressively, beginning with the most tolerable modality—for example, ambient temperature adjustment before introducing soundscapes—to build comfort and consistency. Patients are instructed to implement changes approximately 2-3 hours before bedtime to allow autonomic adjustment and signal the approaching sleep period.

7.4. Integration of Sensory Interventions into CBT-I

Integrating sensory-based strategies into CBT-I may enhance treatment outcomes, though controlled trials are needed. When clinicians deliver standard CBT-I interventions to patients with sensory hypersensitivity, or when progress plateaus, adjunctive sensory-based interventions including targeted modifications in light, sound, or temperature can be considered based on the individual's sensory profile. These sensory-based interventions should be personalized and guided by validated assessment tools, such as the Sensory Profile (SP) for pediatric patients [120], or Adolescent/Adult Sensory Profile (AASP) for adolescent and adult patients [156]. Embedding these tailored sensory supports into patients' daily routines and home environments allows the therapeutic gains of CBT-I to generalize beyond the sleep environment, improving adherence, self-regulation, and overall well-being. Clinical judgment should guide implementation, considering contraindications in some populations (Table 4).

Table 4. Integration of Sensory Interventions into CBT-I Framework. These integration strategies represent a clinical framework requiring validation through controlled trials comparing combined CBT-I plus sensory interventions to CBT-I alone.

Step	Action	Purpose / Clinical Rationale	Evidence Basis	Example
Step 1	Deliver standard CBT-I modules.	Establish behavioral and cognitive foundations for sleep improvement.	Established (meta-analysis of 241 RCTs, n>30,000) [147]	Weekly sessions addressing sleep-wake schedule consolidation, challenging catastrophic thoughts about sleep.
Step 2	Introduce targeted sensory adjustments (light, sound, or	Address residual sensory contributors to hyperarousal or poor sleep consolidation.	Emerging (small RCTs and pilot studies) [163,164]	Adding blue-blocking glasses 2 hours pre-bedtime for patients with

	temperature) when progress stalls.			evening light exposure; introducing white noise for noise-sensitive patients.
Step 3	Tailor sensory interventions to the patient's unique sensory profile, assessed via occupational therapy tools.	Personalize treatment for greater adherence and symptom improvement.	Theoretical framework with partial empirical support [50,165,166]	For sensory-sensitive patients: dim light (<30 lux), soft pink noise (35-65 dB), moderate cooling (17-20°C). For low-registration patients: bright morning light (2,000-10,000 lux), white noise, larger temperature contrasts.
Step 4	Embed these strategies into daily occupational routines, ensuring consistency and generalization.	Promote sustained behavioral change and long-term maintenance of sleep gains.	Emerging (neurodivergent populations) [167,168]	Establishing 30-minute wind-down routine: dim lights at 9pm, activate sound machine, adjust thermostat to 68°F, maintain nightly consistency

It is worth noting that the sensory-based strategies do not replace CBT-I but rather complement and reinforce it to increase adherence and promote effectiveness. When combined with CBT-I, individualized sensory therapies could provide an inter-sensory buffer against physiological arousal, increasing the likelihood of sustained improvements in sleep and daytime functioning.

8. Conclusions

Sensory-based modalities such as light, sound, and temperature offer non-invasive, accessible, and adaptable ways to promote sleep health. However, the current evidence remains preliminary and heterogeneous across populations and outcomes. Further independent, well-controlled research is needed to clarify long-term efficacy and mechanisms. Their non-pharmacological nature makes them clinically appealing for individuals who do not tolerate or respond to medication. These techniques include dimming evening light, using consistent bedtime soundscapes, lowering core body temperature during asleep, and controlling ambient thermal comfort, all of which shape the sensory environment to promote restorative sleep. These strategies are adaptable across different age groups, neurodivergent populations, and settings including homes and long-term care facilities. When combined with CBT-I, they may serve as environmental cues that help regulate arousal, enhance self-management, and improve adherence.

Despite promising but variable evidence for sensory-based interventions on sleep, several barriers limit widespread clinical adoption and patient adherence. High costs, limited insurance coverage, and disparities in digital literacy and technology access can restrict availability. Adherence remains understudied, with common barriers including initial discomfort, lack of immediate sleep improvement, partner or household disruptions, and insufficient follow-up after initial instruction. Strategies to improve adherence include gradual introduction with clear expectations, involvement of household members in planning, scheduled follow-up for troubleshooting, and integration with CBT-I protocols emphasizing routine and consistency. Because sensory preferences differ across cultures and individuals, patient-centered tailoring and flexibility are critical.

Several knowledge gaps persist. First, existing trials vary widely in design, population, and outcome measures, limiting comparability. Secondly, most studies assess short-term benefits rather than long-term adherence and generalization to daily life. Third, integrations among sensory modalities – light, sound, and temperature – remain poorly understood. Further pragmatic, head-to-head trials testing multimodal sensory interventions with standardized metrics are warranted to inform clinical guidelines. Bridging these gaps will strengthen clinical confidence, refine protocols, and establish sensory-based approaches as a valuable complement to standard behavioral therapies such as CBT-I.

Author Contributions: Conceptualization, Z.S.; Writing - original draft, S.S. and M.M.; Writing - review & editing, S.S. and K.A.G.; Tables and figures, M.M. and Z.T.; Supervision, S.S., K.A.G. and Z.S. All authors reviewed and approved the final manuscript.

Acknowledgement: This study was supported by Sleep Sanity, LLC.

Disclosures: S.S. and K.A.G. served as scientific consultants for Sleep Sanity, LLC. S.Z. is the Chief Executive Officer of Sleep Sanity, LLC. The authors declare no other conflicts of interest.

Data Availability: Not applicable.

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