REVIEW ARTICLES

Systematic review: auditory stimulation and sleep

Elizabeth Capezuti, PhD, RN, FAAN[1]; Kevin Pain[2]; Evelyn Alamag, BS[1]; XinQing Chen, BS[1]; Valicia Philibert, MS, RN[3]; Ana C. Krieger, MD, MPH[4]

[1]Hunter College of the City University of New York, New York, New York; [2]Weill Cornell Medical College, New York, New York; [3]Bronx Veteran Affairs Medical Center; [4]Departments of Medicine, Neurology, and Genetic Medicine, Weill Cornell Medical College, New York, New York

Study Objectives: Auditory stimulation devices (white and pink noise) are used to mask sounds and facilitate relaxation and sleep; however, the effectiveness of this intervention is not well established. This systematic review examined the scientific literature for the effect of specific types of auditory stimulation on sleep outcomes in adults.

Methods: The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement guided this review. Searches were conducted in 9 databases for intervention studies that could easily be employed in clinical practice. We excluded other types of auditory stimulation (music alone, binaural tones, and synchronization). Two reviewers screened abstracts and full-text articles for eligibility, with conflicts resolved by a third reviewer, and extracted data. Risk of bias was assessed with the Effective Public Health Practice Project Quality Assessment Tool for Quantitative Studies.

Results: Thirty-four studies reported results of 1,103 persons participating in 3 categories of interventions: white noise (18), pink noise (11), and 6 multiaudio (some combination of white, pink, music, or silence). Nineteen studies had positive findings in terms of improving sleep outcomes: 6 white noise (33%), 9 pink noise (81.9%), and 4 multiaudio (66.7%). Multiaudio had the lowest (better) risk of bias (mean/standard deviation: 1.67/0.82) compared to white (2.38/0.69) and pink noise (2.36/0.81).

Conclusions: Although there was no strong evidence to support use of auditory stimulation, none of the studies reported any adverse effects with short-term application of auditory stimulation during sleep. Future research needs to include confounding factors that can affect outcomes, including one's noise sensitivity, personality, and other conditions or medications that may affect sleep.

Keywords: systematic review, sleep, sleep quality, white noise, pink noise, music, insomnia

Citation: Capezuti E, Pain K, Alamag E, Chen XQ, Philibert V, Krieger AC. Systematic review: auditory stimulation and sleep. *J Clin Sleep Med*. 2022;18(6):1697–1709.

INTRODUCTION

Although consciousness is reduced during sleep, the auditory system continues to evaluate sounds in the environment by changing brain wave patterns, boosting delta patterns, and augmenting sleep spindles during non–rapid eye movement sleep.[1,2] Ambient sound or external noise may adversely affect sleep both in a person's home or an institutional (eg, hotel, hospital, nursing home, etc) environment.[3,4] Sleep disturbance depends on the stage of sleep, background sound level, and individual factors such as hearing ability.[2] Despite the frequent use of barriers to absorb (eg, acoustic wall panels) or reduce (eg, soundproof windows) sound, none of them effectively overcome all noises. As a result, measures to mask sounds through various forms of auditory stimulation have been used to reduce the undesirable effects of noise and facilitate sleep. It is theorized that insomnia is due to altered neuronal activity in structures of the thalamus, prefrontal cortex, parietal lobe, brain stem, cerebellum, and caudate nucleus,[5] and that auditory stimulation works by improving the functional connectivity among these brain areas.[6]

Auditory stimulation approaches include the use of white and pink noise, as well as music, binaural tones, and sound synchronization. Despite the fact that noise is defined as an unwanted sound, white and pink "noise" are terms commonly used in the clinical literature and commercial products.[7] White noise results from combining sounds of all different frequencies so that the intensity is the same at every frequency. It is analogous to white light, which contains all visible frequencies. It is most often used to mask unwanted sounds such as background noise on a hospital unit or in an office because, as the most intense sensory stimulus, it will decrease the audibility of background sounds.[8] It is also used to treat tinnitus (ringing in the ears)[9] and hyperacusis (an increased sensitivity to normal environmental sounds).[10] Examples include television static, steam hissing from a radiator or humidifier, or the whir of a fan. Commercial white noise generators mimic these sounds with brief, prerecorded audio-tracks that repeat at the end of the track.

Pink noise also contains all frequencies that the human ear can hear, but the intensity of the sound decreases as frequency increases. It increases the lower frequency range so that bass frequencies are louder and higher frequencies are turned down. This is considered equivalent to the spectrum of natural sound.[11] Examples include nature sounds, such as waves lapping on the beach, leaves rustling in the trees, or a steady rainfall.

Multiaudio interventions use either white or pink noise in combination with music or silence. Music is meant to promote muscle relaxation and provide a distraction from other sounds or inhibit intrusive, distressing thoughts about life situations. Soothing, relaxing music used to promote sleep is usually lyric-free with a

slow beat (a rhythm of about 60–80 beats per minute) played from a speaker, headphones, or earbuds.[12] It has been shown to result in decreased heart rate, respiratory rate, and blood pressure, thus indicating relaxation and reduced stress.[13] Other auditory interventions are binaural tones and synchronization. Binaural tones or beats plays 2 different sounds in each ear, with frequencies lower than 1500 Hz and fewer than 40 Hz between the two. Sound synchronization plays audio that matches brainwaves indicated by neurofeedback.[14,15]

Phone apps, smart speakers (eg, Amazon Echo, Seattle WA), and sound machines or conditioners employing white or pink noise are in increasing use, but the effectiveness of these devices in initiating or maintaining sleep is not well established. Nonetheless, these devices may provide an easily employed intervention to improve sleep quality. The purpose of this systematic review was to examine the scientific literature for the effect of select auditory stimulation interventions (white noise, pink noise, or a combination) on sleep outcomes in adults.

METHODS

Literature search
The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used to guide this review.[16] A library specialist (K.P.) performed systematic searches of MEDLINE, Embase, CINAHL, PsycINFO, Scopus, Engineering Village, IEEE Xplore, and the Cochrane Library for all available years through February 1, 2021. Major search terms for all databases included both controlled vocabulary and keywords (Table 1) on the topic of auditory stimulation and sleep. Complete database search strategies are available in the supplemental material.

Study selection and classification
Table 2 describes the inclusion/exclusion criteria. Searches, where appropriate, were restricted to adult, English-language studies but were not otherwise limited by study design, setting, or date of publication. Since we were interested in interventions that could easily be employed in clinical practice, we excluded music by itself, binaural tones, and those that conveyed auditory interventions based on neurofeedback (synchronization). Since there were few studies, we also included abstracts from scientific meetings.

The search results were uploaded to a web-based software platform, Covidence.[17] As indicated in the PRISMA diagram (Figure 1), after 695 duplicates were removed, 2 reviewers (E.A., E.C., or X.Q.C.) independently screened 3,649 titles/abstracts with 1 coauthor (A.K.) resolving any conflicts. This resulted in the exclusion of 3,555 studies that did not meet the inclusion criteria. The remaining 94 full-text studies were accessed by 2 reviewers (E.A., E.C., X.Q.C., or V.P.) for eligibility and another (A.K.) made the final determination. Sixty studies were excluded since they were the wrong study type (25; lay article, study protocol, letter, literature summary), the wrong intervention (21), were duplicates (5), dissertations (2), in another language (3), used the wrong design (2), or did not measure a sleep outcome (2). This resulted in 34 articles retained for this review.

Data extraction
Two research assistants (RAs: E.A., X.Q.C.) extracted the study characteristics of each study onto an Excel worksheet. One

Table 1—Search terms.

Concept[a]	Keywords[b]	Controlled Vocabulary[c]
1. Auditory stimulation	((white or pink) adj2 noise) or (sound* adj2 (ambient or enrichment or generator* or nature or modulat* or therap* or masking or condition* or broadband or oscillat*)) or (stimulat* adj2 (acoustic or auditory)) or (soundscape* or binaural beat* or audio* relax*) or (noise* adj (mask* or block*)) or ((sleep adj (machine* or device* or app or apps)) and (sound* or noise*))	Medline and Cochrane: Acoustic Stimulation Embase: auditory stimulation CINAHL: Acoustic Stimulation PsycINFO: Auditory Stimulation or White Noise or Auditory Masking
2. Sleep	(sleep* or insomnia* or circadian or "biological clock*" or "night* wak*" or "night* awak*")	Medline and Cochrane: exp Sleep or exp Sleep Wake Disorders Embase: exp sleep or exp sleep disorder CINAHL: Sleep+ or Sleep Disorders+ PsycINFO: Sleep or Napping or NREM Sleep or REM Sleep or Sleep Disorders or Hypersomnia or Insomnia or Kleine Levin Syndrome or Narcolepsy or Parasomnias or Sleepwalking
3. Tinnitus	(tinnitus or tinnitis)	Medline and Cochrane: Tinnitus Embase: tinnitus CINAHL: Tinnitus PsycINFO: Tinnitus

Search term modifiers: * = truncation, adj = adjacency, () = nested terms, "" = locked terms, exp = narrower terms included. [a]Search term concepts were combined using Boolean operators: (1 AND 2) NOT 3. Full search strategies for each database are available in the supplemental material. [b]Keywords were searched in all available text fields across 8 databases: Medline, Embase, CINAHL, PsycINFO, Cochrane, Engineering Village, Scopus, and IEEE Xplore. [c]Controlled vocabulary terms were used only per specified database.

Table 2—Inclusion and exclusion criteria.

| Inclusion Criteria	Exclusion Criteria
• Intervention studies of white noise* or pink noise** alone or in combination with other auditory stimulation with a sleep-related outcome (objective or self-reported) • Any intervention design type or sample size • Adult participants • English language	• Fetuses, infants, children, or adolescents • Correlational studies, narrative reviews, editorials, letters to the editor, books, book chapters, dissertations, lay magazine articles • Published study protocol • Auditory intervention that is a heartbeat simulator, metronome, music, lullaby, binaural tones, or that uses synchronization • Non-English language

*White noise includes sound generators that mimic television static, steam hissing from a radiator or humidifier, or the whir of a fan. **Pink noise includes nature sounds such as waves lapping on the beach, leaves rustling in the trees, or a steady rainfall.

author (E.C.) checked 10 article extractions and reviewed errors with the RAs. Then each RA checked the other while 1 author (E.C.) randomly reviewed 25% of articles until there was 100% agreement. The authors worked independently in the research, data collection, and risk of bias assessment. Audio interventions were categorized into 3 categories: white noise, pink noise, and multiaudio.

Methodological quality assessment

The 2 RAs also assessed study quality with the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool (QAT) for Quantitative Studies[18] and another coauthor discussed any discrepancies until consensus was reached. The QAT includes 7 domains: selection bias, study design, confounders, blinding, data collection methods, withdrawals and

Figure 1—PRISMA flow diagram.
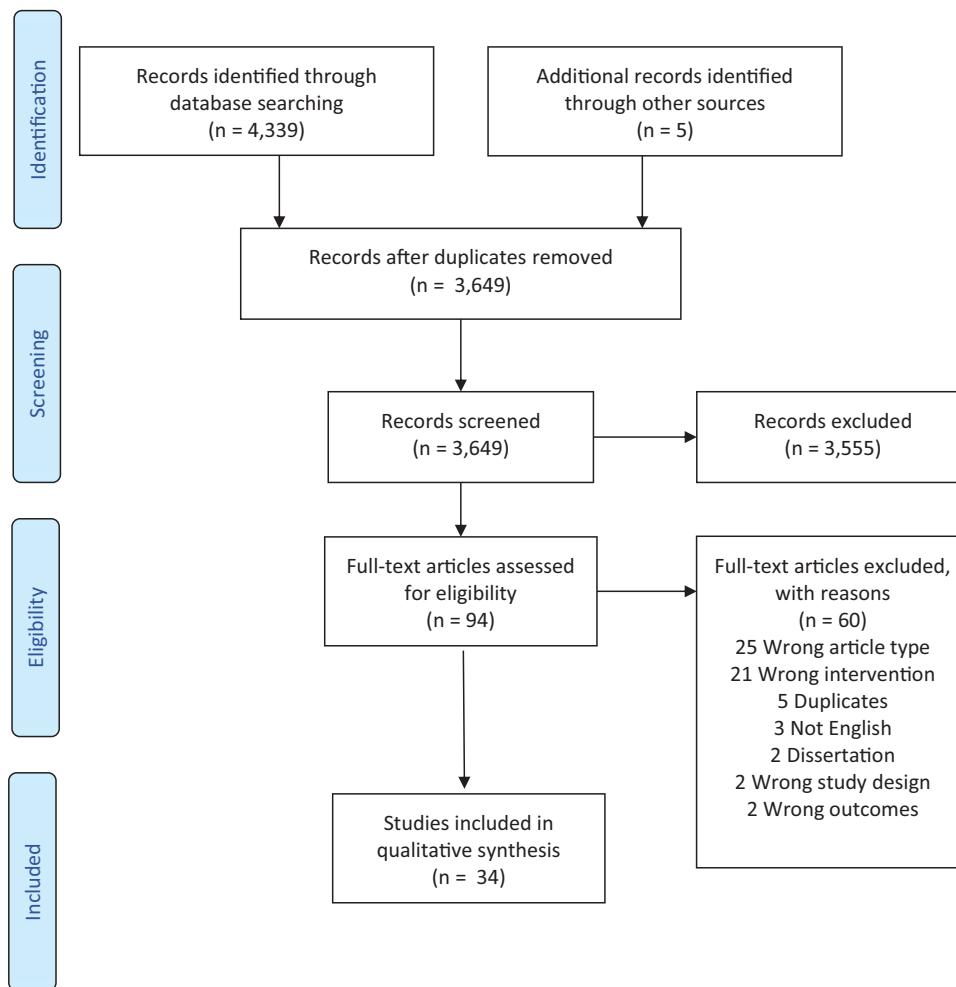
dropouts, and intervention integrity. The cumulative score provided a global rating of 1 (strong or no weak ratings), 2 (moderate or 1 weak rating), or 3 (weak or 2 or more weak ratings). The QAT has content and construct validity and acceptable test-retest reliability (kappa = 0.74 and interrater reliability (kappa = 0.61).[19] Additionally, we compared studies by how sleep was measured, specifically if objective measures were used; we further differentiated if measured by the gold standard of polysomnography or by actigraphy, which is known to overestimate total sleep time and efficiency and underestimate sleep onset.

RESULTS

Overview of the included studies

The 34 studies that met criteria included 27 articles[8,11,20–44] and 7 abstracts[45–51] published between 1988 and 2021. The characteristics of included studies are presented in **Table 3**. A third of all studies were randomized controlled trials (RCTs) (12) or controlled clinical trials (2), while the other study designs included cohort (18), cohort analytic (1), and a 2 × 3 design (1). Most (n = 28) studies excluded those with any sleep problems or did not screen for sleep problems, while 7 studies included those with insomnia.[22,25,28,31,32,34,44] Nine studies specifically excluded those with hearing problems, while 1 included those with tinnitus,[28] and the remainder did not indicate it as an exclusion criterion. One study included participants with dementia.[43]

Most interventions were implemented in a lab (15) or hospital (12, with 4 on critical care units) in North America (19). Others took place in Asia (6), Europe (6) and the Middle East (3). There was a total of 1,103 participants with a mean number of 32.44 (standard deviation [SD] = 21.21) per study and a range of 4–105 participants. Of the 24 studies reporting age, the mean was 56.7 years (SD = 18.88) with a range of 17–70 years. Among the 29 studies that included sex, the mean proportion of women was 52.12%. Twenty-four studies described the race/ethnicity of participants as White (11), Asian (5), and 2 mixed (White, African American, Hispanic, and American Indian).

From the 34 articles that met criteria, a total of 35 (Montgomery-Downs et al[32] compared white to pink noise) interventions were identified: white noise (18), pink noise (11), and 6 multiaudio (some combination of white, pink, music and/or silence). The duration of the auditory intervention, reported in 26 studies, was an average of 267.04 minutes (SD = 225.94; range: 30–750) with 13 providing sound all night (360–750 minutes), while the others provided sound for 30–120 minutes prior to sleep initiation (13). Most studies (19) provided sound intensity with an average of 56.38 dB (SD = 13.68; range = 30–93), while only 8 studies indicated sound frequency with an average of 82.43 (SD = 170.85; median = 31; range = 1–500) Hz. Five studies provided both sound intensity and frequency, 14 indicated only intensity, 3 reported only frequency, and 12 studies did not indicate either sound intensity or frequency.

In half (17) of the studies, a single measure for sleep outcome was used, including objective measurements such as polysomnography (PSG; 16), actigraphy (5), cortisol/melatonin urine

levels (2), or melatonin (1) or cortisol (1) saliva levels. Others used validated self-reports: The Pittsburgh Sleep Quality Index (4),[52] Richards-Campbell Sleep Questionnaire (4),[53] Verran and Snyder-Halpern Sleep Scale (1),[54] The Profile of Mood States (1),[55] Patient-Reported Outcomes Measurement Information System survey (1),[56] the Insomnia Severity Index (1),[57] and the Stanford Sleepiness Scale (1).[58] Four studies used a sleep diary or log and another 10 used investigator-developed tools. Among sleep outcomes, onset latency (15), sleep maintenance (16), slow wave activity (14), and/or total sleep time (10) were reported.

Nineteen (56%) studies showed an improvement in sleep: 6 (38%) white noise, 4 (66.7%) multiaudio, and 9 (81.9%) pink noise. Improvements were observed in slow wave activity (8), wake time after sleep onset (8), sleep latency (7), duration (4), efficiency (3), as well as 9 studies reporting positive perceptions of sleep quality. The proportion of positive findings was similar in a simulated lab environment (50%) vs those conducted in either a community or institutional setting (59%).

Methodological quality assessment

Table 4 summarizes the QAT global rating score, study design, objective sleep measure, and whether the intervention improved sleep quality. The QAT risk of bias varied across studies with 6 studies scoring "1," 14 scoring "2," and 15 scoring "3" (lower scores indicate less bias). The average score (range 1–3) was 2.29 (0.76) with most studies not reporting that either the assessor or the participant was blinded. Also, since 8 studies were presented in a conference abstract, we were not able to determine risks of confounding or the rate of withdrawals/dropouts in those studies. When the QAT global rating score was compared by audio type, multiaudio (mean [M]/SD = 1.67/0.82) intervention studies had the lowest (better) quality ratings vs the white noise (M/SD = 2.38/0.69) and pink noise (M/SD = 2.36/0.81) studies. Thus, multiaudio had the best risk of bias scores. Although most studies examined white noise (20), white noise had the lowest proportion of positive findings and highest risk of bias.

Comparison of studies by category

From the 18 white noise studies, we identified 2 studies with a low risk of bias (11.1%), 7 RCTs (38.9%), with 8 employing PSG. The 2 low-risk studies reported no[32] or mixed results.[31] Of the 7 studies of moderate risk of bias, 2 had a positive, 2 a mixed, 2 none, and 1 a negative result. Of the 9 studies conducted in a lab, only 1 had positive results,[44] while 5 of 9 studies in a hospital or home had positive results. White noise was produced with either a sound generator, a low-frequency fan, or a recording of a fan motor. Twelve (66.7%) studies reported intensity of the sound with a range from 38 to 84 dB and a mean of 55.55 dB (SD = 14.65). Frequency ranged from 22 to 500 Hz (M/SD = 140/202) among the 5 studies reporting Hz. Of the 14 studies reporting duration, most exposed participants to the sound all night (9); however only 4 had positive results.[25,28,37,49]

Most (9) of the 11 pink noise studies reported positive sleep outcomes. However, only 2 studies had a low risk of bias[32,33];

Table 3—Characteristics of included studies (n = 34).

Study	Intervention Description	Design, Setting, and Location	Sample Size; Participant Inclusion Criteria [Mean Age (SD, Range), % Women]	Sleep Measure(s) Risk of Bias (RoB)*	Sleep Result (Positive, Mixed, None, Negative) and Specific Outcomes for Intervention Group
White Noise (n = 18)					
Alkahtani 2019[8]	White noise (simulated air conditioner sound at 43 dB) to mask ambient sounds	Cohort; Community–home; Saudi Arabia–Riyadh	n = 48. Healthy young adults not disturbed by night noises, had sleep disorder or hearing problem. Age 21.3 (1.9, 18–25); 58.9% women	Actigraphy, Sleep diary RoB = 2	None. No improvement in sleep latency, duration, efficiency, WASO, or sleep quality
Daum 1988[21]	White noise–monotonous stimulation of 186 tones (each for 2 seconds) for 40 minutes, 500 Hz at 38 dB vs silence	2 × 3 factorial design; Lab; Europe–Germany	n = 55. Healthy male university students; Age 18–22; 0% woman**	PSG RoB = 3	None. No significant differences in sleep latency
Ebben 2021[22]	White noise to mask sounds	Cohort; Community–home; USA-NY	n = 8. Complaints of noise disturbing sleep; Age 39–74: 62.5% women	Actigraphy, Sleep log RoB = 2	Positive. Reduced WASO and awakenings from sleep
Farokhnezhad 2016[23]	White noise to mask hospital sounds for 120 minutes at 40–50 dB	Cohort analytic; Hospital–CCU; Iran-Tehran	n = 60. > 30 years older on CCU at least 3 nights; Age 58.9 (10.9); 43.3% women**	PSQI, Sleep log RoB = 2	Mixed. Improved perceived sleep quality but no change in total sleep time
Forquer 2007[25]	White noise–generator for 480 minutes at 60–75 dB	Cohort; Community–college dorm rooms; USA-MI	n = 4. With sleep latency > 30 minutes and/or wakes up > 1/ night. Age 19, 75% women	Sleep diary, Sleep survey RoB = 3	Positive. Reduced sleep latency and night awakenings
Gao 2020[26]	White noise vs REM brain-wave music vs SWS brain-wave music × 20 min for 6 days	RCT (3 groups); Sleep center; China	n = 33. History of staying up late, right-handed with subhealthy sleep quality; Age 21.4 (5.6), 48.5% women	PSG RoB = 3	None. Nonsignificant sleep efficacy decreased in white noise and REM and increased in SWS group
Handscomb 2006[28]	White noise sound generator–heartbeat, nature sounds for 480 minutes	Cohort; Hospital; Europe-UK	n = 35. With complaints tinnitus-related sleep problems; Age 52.9 (28–78); 71.8% women	PSQI RoB = 2	Positive. Improved perceived sleep quality
Messineo 2017[31]	White noise–broadband sound at 46 dB	RCT; Lab; USA-MA	n = 18. Exclude if history of insomnia or drug use that impairs sleep; Age 28.5 (13.5, 20–65); 50% women**	PSG, Visual analog scale for sleep quality, Stanford Sleepiness Scale RoB = 1	Mixed. Reduced N2 sleep latency but not latency to stage N3
Montgomery-Downs 2010[32]***	White noise–low frequency fan for 480 minutes < 50 Hz with subtle heartbeat < 100 Hz at 63 dB vs Pink Noise (nature sounds) > 2000 Hz at < 50 dB	Cohort; Community-home; USA-VA	n = 25. History of insomnia but not any other sleep disorder; Age 40 (14); 64% women**	Actigraphy, PSQI RoB = 1	None. None for white noise and mixed for Pink. Positive for improvements in sleep latency for pink noise but reduced duration.

Table 3—Characteristics of included studies (n = 34). (*Continued*)

Study	Intervention Description	Design, Setting, and Location	Sample Size; Participant Inclusion Criteria [Mean Age (SD, Range), % Women]	Sleep Measure(s) Risk of Bias (RoB)*	Sleep Result (Positive, Mixed, None, Negative) and Specific Outcomes for Intervention Group
Owen 2019[45] Abstract	Active noise cancelling headphones with white noise masking for 1 night and 1 night no intervention	Randomized crossover; Hospital–ICU; England	n = 14; Critically ill, nondelirious adults not receiving ventilation	Richards-Campbell Sleep Questionnaire RoB = 3	None. No significant differences in sleep (5.7 score improvement in intervention group, *P* = .55)
Shaikh 2017[49] Abstract	Masking sound for 360 minutes that reduced environmental sound from > 75 dB to 60.3 (0.5) dB	Cohort; Hospital–ICU; USA-IL	n = 5. Adults weaning from prolonged mechanical ventilation in ICU without hearing problems, delirium, sedation or agitation	PSG, Survey RoB = 3	Positive. Improved sleep efficiency–fewer episodes of awakening to a sound event (9% vs 21%); 3/5 participants reported improved sleep quality and 2 with no difference
Stanchina 2005[37]	White noise mixed in with ICU noise for 480 minutes, 22.05 KHz, 62 dB	Cohort; Hospital; USA-RI	n = 5. No history of sleep problems; Age 27 (1.7, 18–65); 40% women	PSG RoB = 3	Positive. Substantially reduced arousals, especially during REM sleep (not NREM) while slow wave sleep with white noise remained the same as baseline (no noise), compared to reduction with ICU noise.
Taranto-Monemurro 2017[51] Abstract	White noise, filtered by 4 speakers at 45.3 (1.2) dB	Cohort; Lab; USA-MA	n = 8.	PSG RoB = 3	Mixed. Positive for reduced sleep latency but no difference in sleep maintenance, total time or slow wave activity
Topf 1992[39]	White noise available for personal control over CCU noise for 480 minutes at 84 dB	RCT; Lab–simulated hospital; USA-CA	n = 105. No hearing or sleeping problems. Age 35.6, 100% women with mixed racial/ethnic groups	PSG, Sleep summary sheets RoB = 2	Negative. Personal control with white noise resulted in poorer sleep efficiency and more difficulty falling and staying asleep
Waye 2004[40]	White noise–low frequency noise for 360 minutes, 50 Hz at 40 dB	Cohort; Lab-Europe	n = 26. Age 26 (4.3); 0% women	Cortisol levels (saliva) and Self-reported Sleep Disturbance Questionnaire RoB = 2	Mixed. No differences with sleep latency and maintenance or changes in cortisol secretion but participants felt more tired in the morning
Webb 1979[41]	White noise–recording of a fan motor for 30 minutes at 70 dB vs intermittent tones for 30 minutes, 80 Hz at 70 dB vs silence	RCT, 3 groups; Lab; USA-FL	n = 48. Age 18–22.	PSG RoB = 2	None. No improvement for white noise while intermittent tones resulted in reduced latency and better sleep maintenance

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Table 3—Characteristics of included studies (n = 34). (*Continued*)

Study	Intervention Description	Design, Setting, and Location	Sample Size; Participant Inclusion Criteria [Mean Age (SD, Range), % Women]	Sleep Measure(s) Risk of Bias (RoB)*	Sleep Result (Positive, Mixed, None, Negative) and Specific Outcomes for Intervention Group
Young 1988[43]	Modified white noise (water) generator at the bedside from 9 PM to 7 AM × 4 nights (4 nights acclimate to lab + 4 night no intervention)	Randomized crossover; Lab; USA-MD	n = 8; Adults > 60 years with Alzheimer's disease and history of nocturnal wandering. Age 70 (60–82); 50% women	Sleep behavioral observation every 30 minutes by nurse RoB = 3	None. No differences in sleep though 2 participants displayed reduced agitation
Zabrecky 2020[44]	White noise–vibroacoustic stimulator included a 24-minute vibroacoustic (8–10 Hz) program twice/week in lab and audio × 60 minutes nightly in bed. Both for 1 month	RCT; Lab twice/week, audio in community-home; USA-PA	n = 30. Adults with insomnia. Age 43.3 (19.6, 27–35); 46.7% women	Actigraphy (5 nights prior and following intervention), Insomnia Severity Index RoB = 3	Positive. Significant improvement in minutes slept and sleep quality.
Multiaudio (n = 6)					
Clark 2017[20]	Multiaudio. Audio sleep menu of white noise machine, music, ear plugs, close door/blinds, tea	Controlled clinical trial; Inpatient for > 1 day; Hospital-Medical unit; USA-VA	n = 62. Age 42–90; 56% women	Sleep Satisfaction Survey RoB = 3	Mixed. Intervention group participants were more satisfied with sleep though men preferred white noise compared to women
Farrehi 2016[24]	Multiaudio. Choice of white noise, sleep mask, or ear plugs	RCT; Hospital-non-ICU for > 4 days; USA-MI	n = 86. Age 56.22 (11.41); 44% women	Patient-Reported Outcomes Measurement Information System survey RoB = 1	Positive. Reported decreased sleep, wake disturbance, and fatigue. White noise used most (50–53%)
Goel 2005[27]	Multiaudio. Bird song with classical music background × 120 minutes at 60 dB	Cohort; Lab; USA-CT	n = 10. Age 44.7 (21.4, 18–72); 50% women	Melatonin (saliva), Profile of Moods States, Fatigue subscale RoB = 2	Positive. Improved fatigue level
Hu 2015[29]	Multiaudio. Classical music and nature sounds in evening (birds) and morning (frogs/waves) × 30 minutes at 69.8 ± 2 dB + eye masks and ear plugs	RCT; Postcardiac surgery without sleep disorder; Hospital-SICU; Asia-China	n = 45. Age 56.6 (11)**; 55.5% women	Nocturnal urine, melatonin, and cortisol levels, Richards-Campbell Sleep Questionnaire RoB = 2	Positive. Increased perceived sleep quality (latency, maintenance, total sleep time and depth); no differences in melatonin or cortisol levels
Rybarczk 2002[34]	Multiaudio. Audio relaxation (music, breathing, nature sounds) at home × 30 minutes for 1 week vs classroom CBT vs control	RCT, 3 groups; Community-Home; USA-IL; Mixed racial/ethnicity	n = 38. Adults > 54 years with insomnia and chronic illness; Age 67.8; 58% women	Actigraphy, PSQI, Sleep logs, Dysfunctional Beliefs and Attitudes About Sleep Scale RoB = 1	Mixed. CBT demonstrated the most improvement in self-reported measures while Multiaudio improved total sleep time, latency, efficiency, and perceived sleep quality. No changes in any group with actigraphy.

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Table 3—Characteristics of included studies (n = 34). (*Continued*)

Study	Intervention Description	Design, Setting, and Location	Sample Size; Participant Inclusion Criteria [Mean Age (SD, Range), % Women]	Sleep Measure(s) Risk of Bias (RoB)*	Sleep Result (Positive, Mixed, None, Negative) and Specific Outcomes for Intervention Group
Ryu 2012[35]	Multiaudio. Music–nature sounds, delta wave control music and Goldberg variations with earphones × 53 minutes + eye bandage vs ear plugs	RCT; Hospital-CCU; South Korea	n = 58. With CAD after PTCA; Age 61.2; 35% women	Verran and Snyder-Halpern Sleep Scale, Quantity of sleeping question-naire RoB = 1	Positive. Both total sleep time and perceived quality of sleep improved.
Pink Noise (n = 11; 1 Compared to White Noise)					
Kawada 1993[30]	Pink Noise—SF-05 noise generator through loudspeaker × 480 minutes at 60 dB	Cohort–within participants design; Lab; Asia-Japan	n = 5. Age 19–28; 25% women	PSG RoB = 3	Positive. Improved sleep latency
Montgomery-Downs 2010[32]***	Pink Noise (nature sounds) > 2000 Hz at < 50 dB vs (see above) White noise–low frequency fan for 480 minutes < 50 Hz with subtle heartbeat < 100 Hz at 63dB vs	Cohort; Community-home; USA-VA	n = 25. History of insomnia but not any other sleep disorder; Age 40 (14); 64% women**	Actigraphy, PSQI RoB = 1	Mixed. Positive for improvements in sleep latency but reduced duration.
Nasari 2018[33]	Nature sounds (rain, birds, forest) with MP player for 30 minutes at 60–70 dB silence (muted headphones) vs control.	RCT (3 groups, single blind); Hospital–CCU; Iran-Tehran	n = 93. No history of sleep disorders, on CCU unit for at least 2 days; Age 56.25 (14); 38.7% women**	Richards-Campbell Sleep Questionnaire RoB = 1	Positive. Both nature sounds and silence improved sleep latency, maintenance, efficiency, and self-reported sleep quality
Papalambros 2015[46] Abstract	Pink Noise, alternating pulses on vs off of 0.8–2.1 Hz	Cohort; Lab; USA-IL	n = 7. Healthy adults older ≥ 50 years; Age 66.85 (10); 85.7% women	PSG (EEG–power spectral analysis) RoB = 3	Mixed. Positive for enhancing slow wave activity during pink noise pulses but no difference between stimulation vs sham night
Santostasi 2017[47] Abstract	Pink Noise	Cohort; Lab; USA-IL	n = 7. Age 66.85 (10); 86.7% women	PSG RoB = 3	Positive. Enhances slow wave activity and spindle amplitude
Santostasi 2015[48] Abstract	50-minute bursts in blocks of 5 of pink noise, then 5 seconds refractory time	Cohort; Lab; USA-IL	n = 4. Healthy young adults; Age 20.3 (1.2)	EEG RoB = 3	Positive. Enhanced slow wave sleep
Simor 2016[50] Abstract	Alternate 1 Hz pulses of pink noise with silence via 1 earplug during NREM sleep	Cohort; Lab: Europe-Hungary	n = 16. Right-handed healthy adults	PSG RoB = 3	Positive. Enhanced slow wave sleep and sleep spindling activity during deep sleep.
Simor 2018[36]	After 5 minutes in daytime NREM sleep, unilaterally given 12 bursts of	Cohort; Lab: Europe-Hungary	n = 35. Right-handed adults with no psychiatric, neurologi-cal, or sleep	PSG RoB = 2	Positive. Enhanced slow wave activity during NREM sleep

Table 3—Characteristics of included studies (n = 34). (*Continued*)

Study	Intervention Description	Design, Setting, and Location	Sample Size; Participant Inclusion Criteria [Mean Age (SD, Range), % Women]	Sleep Measure(s) Risk of Bias (RoB)*	Sleep Result (Positive, Mixed, None, Negative) and Specific Outcomes for Intervention Group
	pink noise at 1 Hz and < 60 dB for 12 seconds, alternated with 15 seconds of silence, × 120 minutes		complaints; Age 27.25 (5.3); 57.1% women		
Suzuki 1991[38]	420 minutes of pink noise at 40–60 dB	Cohort; Lab; Asia-Japan	n = 6. Age 21–28; 25% women	PSG RoB = 3	Positive. Deepened mean sleep depth at 60 dB vs 35 dB and decrease in sleep latency
Williamson 1992[42]	Ocean sounds for 750 minutes	RCT; Hospital; USA-AL	n = 56. No sleep disorders or repeat CABG. Age 58.6 (7.7, 35–69); 30% women**	Richards-Campbell Sleep Questionnaire RoB = 2	Positive. Greater perceived sleep latency, maintenance, deeper and total sleep
Zhou 2012[11]	Pink Noise–brain activity synchronization with 10 min quiet + 10 min pink noise × 50 minutes (group 1); 480 minutes (group 2); afternoon 60 minutes	Cohort, 3 groups; Lab; Asia-China	n = 40. Age 21–30; 50% women	PSG, Sleep quality questionnaire RoB = 2	Positive. Increased stable sleep time (maintenance) and self-reported sleep quality

*The Risk of Bias is the summary score of the Effective Public Health Practice Project–Quality Assessment Tool for Quantitative Studies. **If total sample demographics not given then only experimental group demographics are listed. ***The study by Montgomery-Downs et al 2010 compared white to pink noise so it appears twice in the table. CABG = coronary artery bypass grafting, CAD = coronary artery disease, CBT = cognitive behavioral therapy, CCU = coronary care unit, EEG = electroencephalogram, ICU = intensive care unit, NREM = non-REM, PSG = polysomnography, PSQI = The Pittsburgh Sleep Quality Index, PTCA = percutaneous transluminal coronary angioplasty, RCT = randomized controlled trial, REM = rapid eye movement, SICU = surgical intensive care unit, SWS = slow wave sleep, WASO = wake time after sleep onset.

1 of which had mixed findings[32] and the other had a positive finding.[33] Seven of the 9 studies with positive findings were conducted in a lab environment. In the 1 study that compared white and pink noise, there was no improvement in sleep among those in the white noise group, while the results from the pink noise group were mixed.[32] In 5 studies, the participants were exposed to pink noise for most of the night (420–750 minutes),[11,30,32,38,42] while others were exposed only during sleep initiation (3; 30–120 minutes)[33,48,50]; the proportion of those with positive findings were similar (4/5 vs 5/6, respectfully). Fewer than half reported sound intensity (5; M/SD = 57/ 6.7) or frequency (4; M/SD = 501/999; range = 1–2000).

The multiaudio interventions had the highest proportion of positive findings and the best risk of bias scores. Of the 6 multiaudio interventions, half had a low risk of bias and used an RCT design,[24,34,35] but none measured sleep with PSG. The combination of audio interventions included either nature sounds plus different types of music (4)[27,29,34,35] or provided a choice to participants of white noise, ear plugs, or music (2).[20,24] Of the

latter, most chose white noise. Four (66.7%) reported positive sleep findings,[24,27,29,35] but there was no consistent pattern of multiaudio type or risk of bias. The sounds were played an average of 58 minutes (SD = 43; range 30–120; n = 4) for an intensity of approximately 65 dB (2), and none reported sound frequency. Only 1 study was conducted in a lab. Of the 4 with positive results, 1 was in a lab. Compared to the white noise group, a higher proportion of those with positive findings had been conducted in a lab (1 out of 4 vs 1 out of 9). The pink noise group had a relatively higher proportion of those with positive findings when studied in the lab (7 out of 9).

DISCUSSION

Overview of the qualitative analyses

Although a quiet environment is suggested for inducing and maintaining sleep, it is not always possible, especially in urban settings. Paradoxically, many have resorted to using music or

Table 4—Methodological quality of studies.

	Global Rating	Design	PSG/ACT
White noise (n = 18)			
Alkahtani 2019[8]	2	Cohort	ACT
Daum 1988[21]	3	2 × 3	PSG
Ebben 2021[22]	2	*Cohort*	*ACT*
Farokhnezhad 2016[23]	2	Cohort analytic	
Forquer 2007[25]	3	*Cohort*	
Gao 2020[26]	3	RCT	PSG
Handscomb 2006[28]	2	*Cohort*	
Messineo 2017[31]	1	RCT	PSG
Montgomery-Downs 2010[32]*	1	Cohort	ACT
Owen 2019[45]	3	RCT	
Shaikh 2017[49]	3	*Cohort*	*PSG*
Stanchina 2005[37]	3	*Cohort*	*PSG*
Taranto-Monemurro 2017[51]	3	Cohort	PSG
Topf 1992[39]	2	RCT	PSG
Waye 2004[40]	2	Cohort	
Webb 1979[41]	2	RCT	PSG
Young 1988[43]	3	RCT	
Zabrecky 2020[44]	3	*RCT*	*ACT*
Multiaudio (n = 6)			
Clark 2017[20]	3	RCT	
Farrehi 2016[24]	1	*RCT*	
Goel 2005[27]	2	*Cohort*	
Hu 2015[29]	2	*RCT*	
Rybarczyk 2002[34]	1	RCT	ACT
Ryu 2012[35]	1	*RCT*	
Pink noise (n = 11)			
Kawada 1993[30]	3	*Cohort*	*PSG*
Montgomery-Downs 2010[32]*	1	Cohort	ACT
Nasari 2018[33]	1	*RCT*	
Papalambros 2015[46]	3	Cohort	PSG
Santostasi 2017[47]	3	*Cohort*	*PSG*
Santostasi 2015[48]	3	*Cohort*	*PSG*
Simor 2016[50]	3	*Cohort*	*PSG*
Simor 2018[36]	2	*Cohort*	*PSG*
Suzuki 1991[38]	3	*Cohort*	*PSG*
Williamson 1992[42]	2	*RCT*	
Zhou 2012[11]	2	*Cohort*	*PSG*
Summary	**No. Positive/Total***	**Percentage Positive**	**Mean/SD Global Rating**
Multiaudio	4/6	66.7	1.67 (0.82)
White noise	7/18	38.0	2.45 (0.69)
Pink noise	9/11	81.8	2.36 (0.80)

Italic rows indicate positive results. Global rating is the summary of the 7 domains of the Effective Public Health Practice Project (EPHPP) Quality Assessment Tool (QAT) for Quantitative Studies. Scores: 1 = strong or no weak ratings, 2 = moderate or one weak rating, or 3 = weak or 2 or more weak ratings. *The study by Montgomery-Downs et al 2010 compared white to pink noise so it appears twice in the table and the total is 35 instead of 34. CCT = controlled clinical trial, PSG/ACT = measured sleep outcomes with polysomnography and/or actigraphy, RCT = randomized controlled trial, SD = standard deviation.

the audio of a television as a sleep aid,[59,60] without describing a clear negative impact on sleep duration or quality.[61] Audio stimulation to induce sleep with sound "conditioners" or "generators" first appeared in the United States in the 1960s and now accounts for over a billion dollars in sales each year.[62] Nonetheless, scientific research has been lacking in this field. This is the first known systematic review to examine the evidence of auditory stimulation effects on sleep outcomes in adults. Our review identified only 34 studies, and the findings are conflicting. Moreover, it was not possible to conduct a meta-analysis due to the variation among study design, measurement, and intervention characteristics.

Delivery of audio stimulation varied by duration of exposure, volume setting, and device (speakers vs earbuds/headphones), making it difficult to compare within and across sound categories. Although this is a scientific review of audio interventions, only 5 studies provided both sound intensity and frequency, thus making it difficult to replicate their study findings.

Most of the studies evaluated white noise, but fewer than a third had positive findings and each of these studies demonstrated moderate or weak risk of bias. The white noise was mostly played all night since the primary function was to mask sounds. However, as others have pointed out, "listening to a sound without meaning can actually be an unpleasant rather than a helpful experience."[28] Comparatively, pink noise may potentially be viewed as more effective than white noise, but the rigor of these studies was poor. This indicates the need for more research, especially since only 1 study compared white to pink noise.[32]

Multiaudio sound had a higher proportion of positive findings with the lowest (better) risk of bias and most used an RCT design. None, however, measured sleep with PSG and there were only 4 positive studies, with a total of 199 participants. Most (5 of 6) studies used a combination of white or pink noise and music. Music is meant to induce sleep by relaxation. It is not possible to test every type of music but to use music perceived as pleasant to the study participant. Several systematic reviews and meta-analyses have reported music as effective for improving self-reported sleep quality among those with both acute and chronic insomnia.[63–65] An online survey, not included in this review, was conducted in the United Kingdom and reported that among 403 respondents who used music at bedtime, younger people who listened to music regularly were significantly more likely to use music to aid sleep. Respondents viewed music as stimulating sleep, part of a normal sleep routine, facilitating a physical or mental state for sleep, and/or blocking internal or external stimuli.[66] A secondary analysis of 15 studies evaluating audio stimulus as a sleep aid found similar results.[67]

Several important methodological issues were identified in this review. Only 5 studies specifically included participants with insomnia complaints[22,25,28,32,34] with only 1 study indicating it was specifically due to environmental noise[22] Also, only 1 study included those with complaints of tinnitus.[32] Further, the exclusion criteria did not account for potentially confounding factors of the participant's usual sleep environment or the testing sites other environmental characteristics (eg, light and humidity levels). Thus, it calls into question the usability of the findings in clinical practice. These conclusions are consistent with another systematic review of studies that examined the association of continuous white noise with sleep.[68]

Implications for clinical practice

Although there is no strong evidence to support use of auditory stimulation, none of the studies reported any adverse effects with short-term application of auditory stimulation during sleep. While 1 study indicated that white noise "induces maladaptive changes in the brain that degrade neurological health and compromise cognition,"[69] there is not enough evidence to support this concern and discourage a patient from using white noise if the person believes it helps with sleep. Among studies conducted in the hospital (not simulated) environment, those using multiaudio[20,24,29,35] had the highest proportion of positive findings (50% within their intervention category) and the lowest risk of bias (1.33/0.6). The 3 positive studies either combined nature sounds with music[29,35] or gave patients the choice of white noise or earplugs.[24]

Hospitals and other institutional patient settings have been working toward reducing overall noise levels,[70] and combining strategies for noise reduction with audio interventions may be effective.[71] The delivery of auditory sounds could be included as part of the hospital television or radio channel choices or the patient's own electronic device; however, this would best work within a single-patient room. In shared rooms, the delivery of sounds by headphones or earplugs could be considered, depending on the patient's level of comfort with these devices. It seems reasonable to ask patients their preference in terms of delivery mode of audio interventions to improve sleep during their hospital stay.

Limitations

We did not include studies of audio interventions that cannot be easily applied in a person's home or a clinical setting, such as binaural tones, and sound synchronization. Furthermore, studies evaluating the effect of music on sleep were also not included since it is difficult to standardize and implement it in an institutional setting due to individual preferences. Our study also did not include newer technologies such as noise "canceling" headphones or earbuds. Given that conference abstracts were included in this review, the risk of bias in these studies may have been underestimated, given that many essential elements of the study methodology were not included in these brief synopses.

Recommendations for future research

This review revealed favorable results with the multiaudio interventions in terms of improving sleep quality, and more studies are needed to compare the various audio interventions individually and in combination. Future research also needs to take into consideration other methodological factors that can affect outcomes, including typical sleeping environment (including those that use television audio, radio, podcasts, or music to sleep), an individual's noise sensitivity and preferences, environmental noise levels, sleep hygiene practices, and any health conditions or medications that may affect sleep. Auditory stimulation also needs to be examined in those with

personality traits that are associated with sleep disturbances, such as those with neuroticism who are highly responsive to environmental stressors as well as those with anxiety and who are perfectionists.[72] Since participants of the studies in this review were mostly young and middle-aged white adults, future studies should address this lack of age and racial/ethnic diversity which may have biased the results.

CONCLUSIONS

Although the use of auditory stimulation interventions to improve sleep is a common practice, there was no clear evidence from this review that it effectively improves sleep. A more rigorous, randomized trial of the various audio interventions among those with insomnia, while controlling for the participant's usual bedtime schedule and environmental factors, would be useful to help determine the potential effect of auditory stimulation on sleep both at home and in institutional settings. For the latter, knowing an individual's preference in terms of audio intervention would also be desirable.

ABBREVIATIONS

PSG, polysomnography
QAT, Quality Assessment Tool for Quantitative Studies
RA, research assistant
RCT, randomized controlled trial
RoB, risk of bias
SD, standard deviation

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SUBMISSION & CORRESPONDENCE INFORMATION

DISCLOSURE STATEMENT

All authors have seen and approved the manuscript. Work for this study was performed at Hunter College and Weill Cornell Medical College. The authors report no conflicts of interest.