Sleep Medicine Reviews 55 (2021) 101385

Contents lists available at ScienceDirect

Sleep Medicine Reviews

journal homepage: www.elsevier.com/locate/smrv

CLINICAL REVIEW

Noise as a sleep aid: A systematic review

Samantha M. Riedy [1], Michael G. Smith [1], Sarah Rocha, Mathias Basner*

Unit for Experimental Psychiatry, Division of Sleep and Chronobiology, University of Pennsylvania Perelman School of Medicine, 423 Guardian Drive, Philadelphia, PA, 19104-6021, USA

ARTICLE INFO

Article history:
Received 30 April 2020
Received in revised form
8 July 2020
Accepted 8 July 2020
Available online 9 September 2020

Keywords:
White noise
Sleep
Bedroom environment
Systematic review
Noise

SUMMARY

White noise is purported to mask disruptive noises in the bedroom environment and be a non-pharmacological approach for promoting sleep and improving sleep quality. We conducted a systematic review of all studies examining the relationships between continuous white noise or similar broadband noise and sleep (*PROSPERO 2020: CRD42020148736*). Animal studies and studies using intermittent white noise to disrupt sleep or enhance slow wave activity were excluded. Two reviewers independently screened titles and abstracts of articles from three databases and assessed risk of bias for the 38 included articles. The primary outcomes described sleep onset latency, sleep fragmentation, sleep quality, and sleep and wake duration. There was heterogeneity in noise characteristics, sleep measurement methodology, adherence to the intervention, control group conditions or interventions, and presence of simultaneous experimental interventions. There was perhaps resultantly variability in research findings, with the extremes being that continuous noise improves or disrupts sleep. Following the GRADE criteria, the quality of evidence for continuous noise improving sleep was very low, which contradicts its widespread use. Additional research with objective sleep measures and detailed descriptions of noise exposure is needed before promoting continuous noise as a sleep aid, especially since it may also negatively affect sleep and hearing.

Introduction

In recent years, there has been a surge in public awareness of the importance of quality sleep for overall health and wellbeing. Results from a survey study conducted by the National Sleep Foundation indicate that at least six in ten Americans report that having a quiet, dark, and cool bedroom environment are three important elements to getting a good night's sleep [1]. To improve the bedroom environment, commercially available devices and smartphone applications purported to mask disruptive noises and improve sleep have been developed. One of the most popular applications is the so-called “white noise machine” (WNM) with at least 250 applications on Google Play for Android devices, in May 2020. WNMs are also available as stand-alone devices, including in-ear buds, similar to headphones, or external devices, similar to alarm clocks.

There are several theories for why WNMs may improve sleep. The first is that the sound emitted has sleep-promoting or wake-reducing properties that lulls the brain into sleep. There is some limited evidence that the sound of rain, for example, which is generally broadband in nature, is as effective as lullabies at facilitating sleep in children [3]. Loewy and colleagues [4] found that both lullabies and broadband sound decrease heart rate and respiratory rate and improve sleep quality among premature infants. The second theory is that white noise could “mask” the presence of other sounds that would otherwise disturb sleep. Masking is a psychoacoustic process by which the threshold for hearing one sound is raised by the presence of a masking sound [7,8]. The human auditory system remains active during sleep, and may thus react to signals perceived as relevant [9]. The probability of the body responding to a noise during sleep increases with the sound pressure level of the acoustic stimulus [10–12]. A reduction in the perceived loudness of noise events by partial masking might therefore result in fewer noise-induced disturbances and less

Abbreviations: CAP, cyclic alternating pattern; dB, decibel; GRADE, grade of recommendations, assessment, development, and evaluation; LOW, Lewis, Olds, Williams critical appraisal tool; NREM, non-rapid eye moment; PICO, participants, interventions, comparators, and outcomes criteria; PRISMA, preferred reporting items for systematic reviews and meta-analyses; PROSPERO, prospective register of systematic reviews; WNM, white noise machine.

* Corresponding author. Unit for Experimental Psychiatry, Division of Sleep and Chronobiology, University of Pennsylvania Perelman School of Medicine, 1019 Blockley Hall, 423 Guardian Drive, Philadelphia, PA 19104, USA. Fax: +1 215 573 6410.

E-mail address: basner@pennmedicine.upenn.edu (M. Basner).

[1] Shared first authorship.

https://doi.org/10.1016/j.smrv.2020.101385
1087-0792/

Glossary of terms

Noise Erratic or statistically random oscillation
Broadband noise Noise whose power spectral density consists of a broad range of frequencies between a defined lower and upper frequency limit.
White noise Noise whose power spectral density is essentially independent of frequency
Pink noise Noise whose power spectral density is inversely proportional to frequency
A-weighting Frequency filter applied to a sound signal to mimic the non-linear response of human hearing at moderate sound pressure levels (approximately 40 dB)
C-weighting Frequency filter applied to a sound signal to mimic the non-linear response of human hearing to impulsive sound and to high sound pressure levels (approximately 80 dB)
Z-weighting Alternatively “flat” or “linear” frequency response, corresponding to an sound signal unweighted in frequency
Decibel Logarithmic measure of the ratio of a sound pressure to the reference sound pressure of the threshold of human hearing (20 μPa). Denoted dB.

fragmented sleep. A third possibility is that white noise functions as a stimulus control [13]. That is, it may act as a cue for sleep that helps individuals fall asleep quickly and maintain sleep.

Conversely, introducing a continuous noise into the bedroom environment could potentially have negative consequences. It could mask relevant sounds in the environment (e.g., a baby crying or alarm) or disrupt sleep itself. Animal studies, for example, have shown that continuous white noise exposure can perturb slow wave sleep and/or rapid eye movement sleep [14]. White noise could also induce hearing loss, if the sound is too loud. Noise-induced hearing loss is a complex mechanism that includes the accumulation of reactive oxygen species and the active stimulation of intracellular stress pathways causing cell death [15]. It is therefore conceivable that, much like the brain, the auditory system needs downtime to clear metabolic byproducts accumulated during waking hours [16]. Finally, white noise could have additional health consequences. Attarha and colleagues [17] concluded in a review of white noise therapy for tinnitus patients using white noise to mask tinnitus rather than external sounds that long-term exposure could result in changes in the functional and structural integrity of the central auditory system and brain.

The term “white noise” is frequently used to describe the general sound emitted by WNMs, AC units, fans, et cetera. *However*, the actual sound emitted may be “white noise”, “pink noise”, or “broadband noise”, each of which has different noise characteristics (see Fig. 1). White noise refers to a sound that has an equal intensity at every frequency f in the frequency range of human hearing (i.e., approximately 20 Hz to 20,000 Hz), and it is perceived as a “hissing” sound. Pink noise refers to sound that has an intensity of $1/f$ at each frequency f. The sound is lower and deeper in character since the lower frequencies are proportionally more intense than the higher frequencies. Broadband noise is an example of filtered noise so it only contains a segment of the entire auditory frequency range, and can sound higher or lower in frequency depending on the limits of the noise band. The term “continuous noise” is used in this article but the sounds described will have varying noise characteristics.

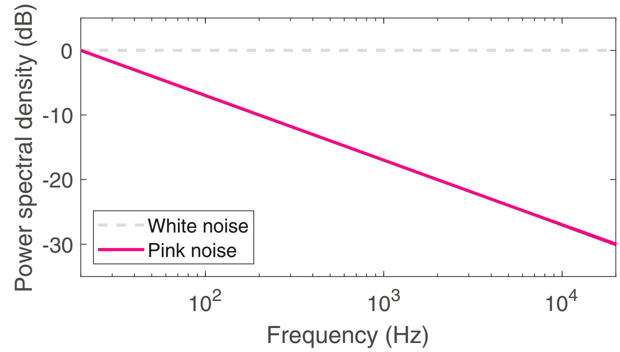

Fig. 1. Power spectral density of white and pink noise. The ordinate shows the relative acoustic energy at each frequency. White noise (dotted gray line) and pink noise (solid pink line) were normalized to have equal energy (0 dB) at 20 Hertz (Hz).

Despite increasing popularity, the efficacy of continuous noise to improve objective and subjective measures of sleep remains unclear. The aim of this study was to systematically review the evidence regarding continuous noise as a non-pharmacological approach for improving sleep among human subjects. Specifically, the review was guided by the *a priori* review question, “Does the use of so-called ‘white noise machines’ improve sleep onset latency, sleep fragmentation, sleep quality and/or decrease arousals, awakenings, and wakefulness?”

Methods

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [18]. The completed checklist can be found in the supplementary materials. The systematic review was registered on the international prospective register of systematic reviews (PROSPERO) database (*CRD42020148736*). A systematic review was conducted over a meta-analysis due to variability in research methods.

Search strategy

Three databases (PubMed, Scopus, and Web of Science) were searched for articles examining the relationship between sleep and continuous white noise, broadband noise, pink noise, or natural broadband sounds (e.g., rainfall). All articles were published prior to the January 23, 2020 search date; the temporal coverage of the search was otherwise only restricted by the capabilities of the databases. The full search strategy can be found in the supplementary materials. The search terms had to be in the title or abstract, and articles had to be written in or translated into English. References in review articles and included articles were reviewed to identify any additional relevant articles.

Study selection

Eligible studies had to meet the following PICO (participants, interventions, comparators, outcomes) PRISMA criteria: Studies had to include human subjects, and noise had to be a continuous stimulus during sleep periods. Studies involving animals, fetuses, intermittent noise or music were excluded. This systematic review focused on continuous noise interventions since research suggests that intermittent noise and the periods of noise onset and offset may actually increase sleep fragmentation and health consequences [60,61]. Bursts of noise are used as arousal stimulus in experimental studies. Furthermore, in order for noise to mask sleep-disruption environmental sounds, it needs to be continuous, since it is unpredictable when such disruptions will occur during the sleep period.

To determine eligibility, two reviewers independently screened the titles and abstracts of all articles against the inclusion criteria. Abstracts without full-text were excluded. The full-text was screened if the abstracts contained insufficient information to determine eligibility. If the reviewers' decisions differed, the final decision was independently decided by a third reviewer (see Fig. 2).

Data extraction

The following variables were extracted from each eligible study by one reviewer and verified by the second reviewer against the original records: article title, authors, journal, year of publication, study purpose, sample size, study population, participant age and sex, inclusion criteria, study setting, noise characteristics (i.e., type, level, duration, and location), number of nights of study participation, sleep measurement methodology, sleep outcomes, statistical analyses, and summarized results. For articles that included noise level measurements but not the frequency weighting, this information was requested from the authors of the articles.

Risk of bias in individual studies

Two reviewers independently assessed the quality of each study using the Lewis, Olds, Williams (LOW) critical appraisal tool [19]. The LOW was chosen over other quality assessment tools since it allows for studies with different methodologies to be evaluated using the same tool. The reviewers discussed any discrepancies in scoring and reached consensus.

Strength of evidence across studies

Two reviewers independently assessed the strength of evidence for the effects of continuous noise on each sleep outcome using the "Grade of recommendations, assessment, development, and evaluation" (GRADE) criteria [20]. This yielded an assessment of whether the strength of evidence for each sleep outcome was of high, moderate, low, or very low quality. The reviewers discussed discrepancies in scoring and reached consensus.

Results

Study selection

A total of 564 articles were identified by searching the three databases and by reviewing the references of included articles and review articles. Two-hundred six articles were excluded for not meeting the PICO criteria. Eleven articles were excluded after reviewing the full-text for not measuring sleep during the study (n = 2), not playing noise during sleep periods (n = 2), being a review article or book chapter that does not include an original research study (n = 2), playing intermittent or bursts of noise rather than continuous noise (n = 2), or the continuous noise was referring to traffic noise (n = 1). Two articles described the same study and results, and one was excluded (n = 1). Thirty-eight articles were included in the qualitative synthesis (see Fig. 2).

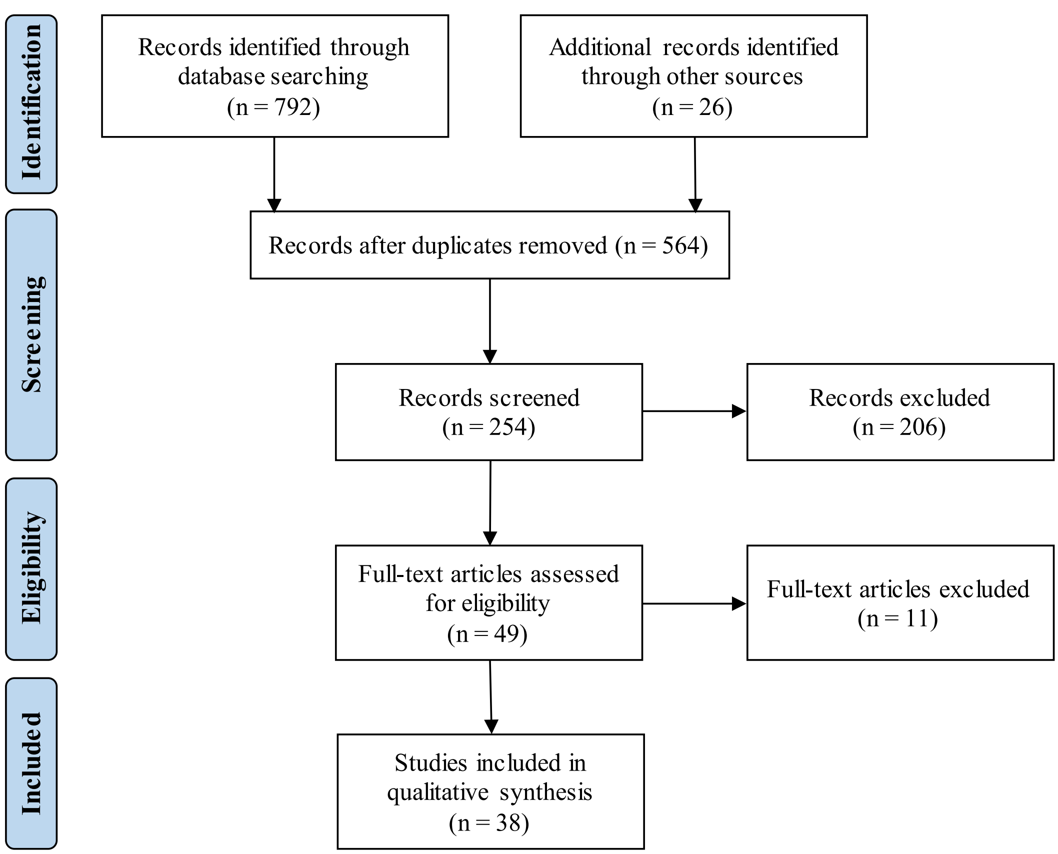

Fig. 2. Four-phase flow diagram for selection of studies using PRISMA selection guidelines.

Study characteristics

Characteristics for each of the 38 included studies are listed in Table 1. Studies were conducted on infants, toddlers, and children (n = 13), adults (n = 10), patients (n = 8), high school or college students (n = 5), mothers (n = 1), and nurses (n = 1). Studies were conducted at home (n = 18), in a laboratory (n = 14), or in a hospital unit (n = 6), with sample sizes of one to 313 participants.

Noise parameters varied substantially across the 38 included studies. The type of noise, noise levels, and noise duration were not always specified (see Table 1). The term "continuous noise" is used throughout the rest of the article despite varying noise characteristics due to the many different types of noise that were studied, and since it was often not exactly clear what kind of noise was used. The types of noise were either described as or determined to be white noise (n = 15), broadband noise (n = 6), air purifier, fan noise, or fan motor (n = 4), variable sounds (n = 4), pink noise (n = 2), 75 Hertz square wave (n = 1), "natural masking" (n = 1), ocean sounds (n = 1), USASI filtered noise (n = 1), sim-music (n = 1), roll or slow surf (n = 1), or a combination of an "approximation of white noise" and variable sounds (n = 1). Noise levels varied from 20 dB to 93 dB and noise generally continued throughout a nighttime sleep period. Noise levels were A-weighted (n = 9), Z-weighted (n = 2), or C-weighted (n = 1) in the twelve studies with known frequency weightings (see Fig. 3).

Sleep outcomes were measured using questionnaires (n = 20), polysomnography or electroencephalography (n = 12), sleep diaries (n = 7), observation (n = 6), actigraphy (n = 3), phone interviews (n = 1), and/or focus groups (n = 1). There was substantial variability in which sleep outcomes were reported. This systematic review focuses on the sleep outcomes describing sleep onset latency, sleep fragmentation, sleep quality, sleep duration, and wake duration. These were frequently reported but importantly they are also consistent with theories for why continuous noise may improve sleep. One could expect a reduction in sleep onset latency and/or sleep fragmentation, which, in turn, may result in greater sleep quality and sleep duration and reduced wake duration. Additional sleep outcomes are listed in Table 1 but are not further discussed.

Synthesis of results

Sleep onset latency

Nineteen studies (50.0%) included sleep onset latency as an outcome (see Tables 1–2). Sleep onset latency was measured among infants and children using observations reported by the parent or study investigator, and it was often referred to as "bedtime struggles" or "resistance in going to bed". Sleep onset latency was measured among patients using self-report, questionnaire, or observations recorded by the study investigator. Otherwise, sleep onset latency was simply defined as the amount of time between bedtime and sleep onset.

The three most common findings were 1) continuous noise reduced sleep onset latency among infants, children, or college students relative to baseline but the effects were not statistically analyzed (n = 5 studies), 2) continuous noise reduced sleep onset latency among students, adults, or patients relative to baseline, a control group, or alternative experimental intervention but the results were not significant (n = 3 studies), and 3) continuous noise reduced sleep onset latency in observation studies where parent(s) or study investigator(s) reported on infants' or patients' sleep (n = 3 studies).

Three studies used continuous noise to contradictorily induce or ameliorate situational insomnia. Terzano and colleagues [50] used continuous noise to induce situational insomnia during nighttime sleep periods, whereas Messineo and colleagues [35] had subjects go to bed 90 min before their usual bedtime and assessed whether continuous noise improved sleep. The hypotheses on the effects of continuous noise were thus in opposite directions, and the findings also varied. Terzano and colleagues [50] found that continuous noise increased sleep onset latency, albeit this effect was not statistically quantified. Messineo and colleagues [35] found that continuous noise significantly decreased sleep onset latency to stage N2 but not stage N1.

Webb and Agnew [52] took a different approach to inducing situational insomnia. Undergraduate students were given 30-min sleep opportunities at approximately ten o'clock in the morning after a full night's sleep. The study was run for five successive days and each day subjects were assigned to one of five conditions: silence, monotonous noise (i.e., continuous fan noise), intermittent tones, tones plus counting, or tones plus eye opening-eye closing. The continuous fan noise did not significantly reduce sleep onset latency relative to silence; however, a substantial proportion of the students did not fall asleep (47.5% with silence; 32.5% with continuous fan noise). The results suggested that continuous noise did not facilitate sleep onset after a full night's sleep and at a time-of-day when the circadian system is increasingly promoting alertness.

Two studies examined the efficacy of multi-component interventions that included continuous noise. Knight and Johnson [33] used an intervention with circadian rhythm management, positive bedtime routines, continuous noise, and graduated extinction to reduce sleep problems in children with autism spectrum disorder. Vesterager [51] used an intervention with hearing aids, WNMs, and psychological therapy to improve symptomology in tinnitus patients, including problems getting to sleep. While the interventions generally reduced sleep onset latency, this reduction may be attributable to other components in the intervention, particularly in the latter study where 26% of patients reported sporadically using WNMs.

Sleep fragmentation

Seventeen studies (44.7%) included sleep fragmentation as an outcome (see Tables 1–2). Actigraphy and polysomnography measures included number of awakenings, sleep bouts, and/or stage shifts; arousal or fragmentation indices; and movement time. Self-report and questionnaire measures included awakenings and/or sleep disturbances. Observation measures included awakenings or interval between startles. The most common findings were that sleep fragmentation was not significantly affected by continuous noise or the effects were not statistically quantified.

Consistent with the theory that continuous noise improves sleep by masking other sounds, Stanchina and colleagues [45] found that recorded intensive care unit sounds increased the arousal index and continuous noise reduced the arousal index of healthy adults, and concluded that the continuous noise increased arousal thresholds by reducing the difference between background noise and peak noise. Of note, however, continuous noise did not reduce sleep fragmentation relative to baseline. In a study with postoperative coronary care artery patients, Williamson [54] found that ocean sounds also significantly improved awakening ratings on the Richards-Campbell Sleep Questionnaire after patients were transferred from the intensive care unit and concluded that they could be used to foster optimal sleep patterns after intensive care unit transfers.

On the other hand, Terzano and colleagues [48] found that while continuous noise did not affect sleep latencies among healthy adults, continuous noise significantly increased sleep fragmentation as assessed by number of stage shifts. Interestingly, they found in a dose response study (45–75 A-weighted dB, with 10-unit

Table 1
Study characteristics by author in alphabetical order (n = 38).

Author, Year	Sample	Subjects[a]	Setting	Noise Parameters			*Sleep Measurement*: Outcome
				Type	Decibels[a]	Duration	
Ashton, 1971 [21]	Neonates	10/22	Lab	75 Hertz square wave	70/48[C]	>2 h	*Observation:* Quiet sleep, active sleep, alert, crying. Quiet sleep, active sleep, and alert states summarized as state epoch durations.
Borkowski et al., 2001 [13]	Exp1: infants Exp2: children	Exp1: 5 Exp2: 4	Home	Exp1: "Approximation" of white noise Exp2: Variable	75	All night	*Sleep diary:* Number of awakenings, bedtime struggles
Brackbill, 1973 [22]	Infants	16	Lab	White noise[+]	85/62	2 h	*Observation:* Quiet sleep, active sleep, drowsy, quiet wake, crying. Total sleep calculated as sum of quiet and active sleep.
Cautilli, 2005 [23]	Infant	1	Home	Air purifier	NS	All night	*Sleep diary:* Number of awakenings
Falkenberg et al., 2003 [24]	Tinnitus patients	173	Home	White noise[+,c]	NS	Varies	*Questionnaire:* Question on whether treatment reduced sleep problems
Farokhnezhad et al., 2016 [25]	Coronary patients	30/30	Hospital	White noise	40–50	1 h	*Questionnaire:* Pittsburgh Sleep Quality Index
Farrehi et al., 2016 [26]	Non-intensive care patients	52/34	Hospital	Variable[+,b]	Varies	Varies	*Questionnaire:* PROMIS fatigue, sleep disturbance, and wake disturbance dimensions
Forquer & Johnson, 2005 [27]	Toddlers	4	Home	White noise	75	All night	*Sleep diary:* Number of awakenings, bedtime struggles duration
Forquer & Johnson, 2007 [28]	College students	4	Home	White noise	60–75	All night	*Sleep diary:* Number of awakenings, sleep onset latency
Forquer et al., 2008 [29]	College students	313	Home	Fan/sound machine[c]	NS	NS	*Questionnaire:* Sleep survey that included questions on sleep patterns, problems, and influencing factors, including questions from the Pittsburgh Sleep Quality Index and Sleep Hygiene Test
Gragert, 1990 [30]	Critical care patients	20/20	Hospital	USASI filtered noise	52/42–52[A]	All night	*Questionnaire:* Richards-Campbell Sleep Questionnaire *Observation:* Number of awakenings, sleep onset latency, total sleep time, sleep efficiency
Handscomb, 2006 [31]	Tinnitus patients	39	Home	Variable	Varies	All night	*Questionnaire:* Pittsburgh Sleep Quality Index
Johnson, 1991 [32]	Infants, toddlers	235	Home	Variable	NS	NS	*Interview:* Telephone interview on resistance going to bed, awakenings, crying episodes, and methods used to ameliorate symptoms, including whether white noise helped sleep
Knight & Johnson, 2014 [33]	Children (ASD)	3	Home	White noise[+]	53–71	All night	*Sleep diary:* Number of awakenings, sleep onset latency
Lee & Gay, 2011 [34]	Mothers	123/88	Home	White noise[b+]	30[A]	All night	*Actigraphy:* Nocturnal sleep hours, sleep efficiency, and wake after sleep onset and daytime sleep minutes *Questionnaire:* General Sleep Disturbance Questionnaire
Messineo et al., 2017 [35]	Healthy adults	18	Home	Broadband	46/40.1	All night	*PSG:* Latencies to N1, N2, N3 and REM sleep, total sleep time, time in sleep stages, sleep efficiency, wake after sleep onset, arousal index, apnea-hypopnea index, SaO_2 *Questionnaire:* Sleep quality visual analogue scale, Stanford Sleepiness Scale
Montgomery–Downs et al., 2010 [36]	Healthy adults	25	Home	Low frequency fan	63	All night	*Actigraphy:* Sleep onset latency, time-in-bed, total sleep time, number and duration of sleep bouts, wake after sleep onset, sleep efficiency, fragmentation index

(*continued on next page*)

Table 1 (*continued*)

Author, Year	Sample	Subjects[a]	Setting	Noise Parameters			*Sleep Measurement*: Outcome
				Type	Decibels[a]	Duration	
Murray & Campbell, 1971 [37]	Newborn infants	12	Lab	White noise	75/45-50	90min, 4x a day	*Questionnaire:* Questionnaire with number and duration of awakenings, and sleep quality scale *Observation:* Wakefulness, irregular sleep, regular sleep, drowsiness, crying, sleep onset latency, interval between startles, length of first regular and irregular sleep
Novak & Auvil-Novak, 1996 [38]	Nurses	45	Home	Variable	NS	NS	*Interview:* Focus group on coping strategies to deal with shift work
Ogata, 1995 [39]	Young adults	8	Lab	Sim-music	88/35[A]	11min 5sec	*PSG:* Time in sleep stages, EEG frequencies *Questionnaire:* Kwansei Gakuin Sleepiness Scale
Rocknathan, 2018 [40]	High school students	18	Home	White noise	NS	1 h	*Actigraphy:* Sleep onset latency, total sleep time, time in sleep stages, time awake, sleep efficiency *EEG:* Sleep onset latency, total sleep time, time in sleep stages, time awake, sleep quality score *Questionnaire:* Pittsburgh Sleep Quality Index, daily survey on sleep quality and naps
Rosalez et al., 2019 [41]	Children (ADHD)	3	Home	White noise	75	All night	*Sleep diary:* Number of awakenings, sleep onset latency
Scott, 1972 [42]	College students	8	Lab	White noise	93±2[A]	All night	*PSG:* Sleep onset latency, REM latency, total sleep time, time in sleep stages, time awake, movement time, number of awakenings, stage shifts
Sezici & Yigit, 2018 [43]	Infants	20/20	Home	White noise[b]	55	Crying stops	*Sleep diary:* Sleep duration, crying duration
Spencer et al., 1990 [44]	Infants	20/20	Lab/hospital	Broadband	67–73	5min	*Observation:* Number of infants that fell asleep within 5 min
Stanchina et al., 2005 [45]	Healthy adults	5	Lab	Broadband noise (1–22 kHz)[b]	61[Z]	All night	*PSG:* Sleep onset latency, time-in-bed, total sleep time, time in sleep stages, awakenings, arousal index
Suzuki et al., 1991 [46]	Adults	Exp1: 1 Exp2: 4	Lab	Pink noise	40-60/35[A]	All night	*PSG:* Sleep onset latency, time in sleep stages, sleep depth, time awake, movement time, stage shifts per hour *Questionnaire:* Subjective sleep question
Terzano et al., 1988 [47]	Healthy young adults	12	Lab	White noise	45[A]	All night	*PSG:* CAP rate, MSLT sleep onset latency *Questionnaire:* Included sleep quality question
Terzano et al., 1990 [48]	Healthy young adults	6	Lab	Broadband	45-75/27.3[A]	All night	*PSG:* CAP rate, MSLT sleep onset latency, total sleep time, sleep period time, wake after sleep onset, time in sleep stages *Questionnaire:* Sleep quality visual analogue scale, Stanford Sleepiness Scale
Terzano et al., 1993 [49]	Healthy young adults	6	Lab	Broadband	55/27.3[A]	All night	*PSG:* CAP rate, sleep onset latency, total sleep time, sleep period time, wake after sleep onset, time in sleep stages *Questionnaire:* Sleep quality visual analogue scale
Terzano et al., 1995 [50]	Healthy adults	6	Lab	Broadband	55/<30[A]	All night	*PSG:* CAP rate, sleep onset latency, REM latency, total sleep time, wake after sleep onset, time in sleep stages *Questionnaire:* Visual analogue scale, St. Mary's Sleep Questionnaire
Vesterager, 1994 [51]	Tinnitus patients	154	Home	Natural masking[+]	NS	NS	*Questionnaire:* Question on problems getting to sleep

Table 1 (*continued*)

Author, Year	Sample	Subjects[a]	Setting	Noise Parameters			*Sleep Measurement*: Outcome
				Type	Decibels[a]	Duration	
Webb & Agnew, 1979 [52]	College students	48	Lab	Fan motor recording	70	30min	*PSG:* Sleep onset latency
Williams et al., 2006 [53]	Children (ASD)	202	Home	White noise	NS	NS	*Questionnaire:* Survey on interventions and medications used to help address child's sleep problems
Williamson, 1992 [54]	Coronary patients	30/30	Hospital	Ocean sound	Varies	All night	*Questionnaire:* Richards-Campbell Sleep Questionnaire
Wolff et al., 1974 [55]	Newborn infants	21	Lab	White noise	92	NS	*PSG:* Cortical evoked response
Young et al., 1997 [56]	Alzheimer's patients	8	Hospital	Roll or slow surf	Mid-range	All night	*Observation:* Sleepiness, restless, awake, bathroom, resting
Zhou et al., 2012 [57]	Adults	40	Lab	Pink noise	20–40[Z]	All night	*ECG-based cardiopulmonary coupling:* Time in sleep stages *Questionnaire:* Sleep quality question

Notes: *Abbreviations:* A-weighted (A), control group received an intervention (*), C-weighted (C), electrocardiogram (ECG), electroencephalography (EEG), experiment (Exp), multi-component intervention (+), polysomnography (PSG), Z-weighted (Z).
Unique study designs: Separate control, dim-light, and ambient noise conditions [21]. ABAB reversal [23,41]. Non-concurrent multiple baseline with ABAB reversal [13] or without ABAB reversal [33,27,28]. Double blind counter-balanced paired nights with a low frequency fan noise and a high frequency birds/insect noise (<50 dB). The high frequency noise was not broadband in its spectral characteristics and was not included [36]. Latin square design with no sound, heartbeat, white noise, white noise bursts [37]. Latin square randomized design including 10 mg zolpidem or placebo with or without white noise [47]. Subjects were exposed to 45, 55, 65, and 75 dBA white noise over four sleep recordings [48]. Subjects had an adaptation night (night 1), placebo drug (night 2), placebo drug with white noise (night 3), and combinations of Brotizolam or Triazolam with or without white noise (nights 4–7) [50]. Subjects received silence, continuous sound, and intermittent tones over five successive sessions [57]. Subjects listed to silence for 5 min, music or sim-music (i.e., modified white noise) for 11min 5sec, and silence again for 5min. Each subject participated in 10 music and 10 sim-music conditions [39]. The effects of white noise were not examined due to inadequate data [40]. No control group [29,32,38,53].

[a] Noise levels for experimental group/comparison group or baseline (if known). Sample sizes for experimental group/comparison group.

[b] Comparison conditions: Swinging intervention [43]. Received multi-component intervention without education on its use or benefits [26]. Received information about how diet can influence sleep and recommendations for healthy eating [34]. Recorded ICU noise [45].

[c] Multi-component interventions: Simultaneous continuous auditory, visual, proprioceptive-tactile, and ambient temperature stimulation [22]. Stress management training and avoidance of silence treated over 1 yr; 82% received white noise generator [24]. Eye mask, earplugs, and white noise machine [26]. Circadian rhythm management, positive bedtime routines, white noise, and graduated extinction [33]. Infant proximity, noise masking, and dim lighting [34]. Hearing aids, supportive psychological therapy, and white noise [51].

steps) within the same subjects that sleep fragmentation continued to increase with increasing sound pressure levels. The results from this study suggest no beneficial effects on sleep onset latency but harmful effects on sleep continuity.

Lee and Gay [34] found among a sample of first time mothers that introducing an intervention with infant proximity, noise masking, and dim lighting during the third trimester had no effect on postpartum sleep disturbance scores. The lack of effect could a result of less than half the mothers reportedly using the device, or

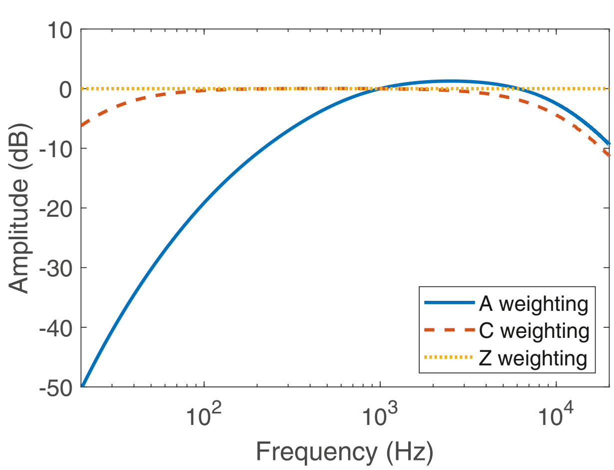

Fig. 3. Frequency weighting filters. A-weighting (blue solid line) and C-weighting (orange dashed line) filters mimic the non-linear response of human hearing at moderate and high sound pressure levels, respectively, by de-emphasizing very low and very high frequencies. Z-weighting (yellow dotted line) corresponds to no frequency filtering. The ordinate shows the attenuation of each frequency.

the control group using components of the intervention. Farrehi and colleagues [26] conducted a study with patients in a non-intensive care unit, where all patients could choose to use an eye mask, earplugs, and/or a WNM. The earplugs attenuated audible frequencies by 20–40 dB. The experimental condition received education on the use and benefits of the sleep-enhancing tools. The education led to greater use of the tools, with 41.2% and 69.2% of patients in the control and experimental groups, respectively, using the tools at least once during the study. That said, the intervention did not significantly improve sleep disturbance scores.

Finally, the effects of continuous noise on sleep fragmentation varied as a function of sleep outcome, sleep measurement, or sleep history in three studies. Continuous noise did not affect stage shifts or movement time among college students in a study by Scott [42], but there was a small albeit significant increase in the number of awakenings. Gragert [30] found that patients reported fewer awakenings with continuous noise but the study investigators did not find significant changes via observation of the patients. Montgomery-Downs [36] found that low frequency fan noise reduced self-reported but not actigraphy-measured sleep fragmentation among healthy young adults.

Sleep quality

Thirteen studies (34.2%) included sleep quality as an outcome (see Tables 1–2). Sleep quality was generally measured as sleep efficiency in actigraphy, polysomnography, and observation studies. Terzano and colleagues [47–50] used an indicator of sleep quality developed by their team [58], termed the Cyclic Alternating Pattern (CAP) rate and described as a measure of arousal instability during non-rapid eye movement (NREM) sleep. Sleep quality was measured in over half of the studies using questionnaires, namely

Table 2
Sleep outcome results by sleep measurement methodology.

First Author, Year	Measure	Effect	Significant	#
Sleep Onset Latency				
Montgomery–Downs, 2010 [36]	Actigraphy	Increased	No	1
Murray, 1971 [37]	Observation	Reduced	Yes	2
Gragert, 1990 [30]	Observation	Reduced	Yes	3
Spencer, 1990 [44]	Observation	Reduced	Yes	4
Scott, 1972 [42]	PSG	No effect	No	5
Terzano, 1990 [48]	PSG	Increased	No	6
Terzano, 1993 [49]	PSG	Increased	No	7
Terzano, 1995 [50]	PSG	Increased	N/A	8
Messineo, 2017 [35]	PSG	Reduced	Varies	9
Webb, 1979 [52]	PSG	Reduced	No	10
Stanchina, 2005 [45]	PSG	Reduced	No	11
Suzuki, 1991 [46]	PSG	Reduced	No	12
Borkowski, 2001 [13]	Sleep Diary	Reduced	N/A	13
Knight, 2014 [33]	Sleep Diary	Reduced	N/A	14
Forquer, 2005 [27]	Sleep Diary	Reduced	N/A	15
Forquer, 2007 [28]	Sleep Diary	Reduced	N/A	16
Rosalez, 2019 [41]	Sleep Diary	Reduced	N/A	17
Gragert, 1990 [30]	Questionnaire	Reduced	Yes	3
Vesterager, 1994 [51]	Questionnaire	Reduced	Varies	18
Williamson, 1992 [54]	Questionnaire	Increased	No	19
Sleep Fragmentation				
Montgomery–Downs, 2010 [36]	Actigraphy	Varies	No	1
Gragert, 1990 [30]	Observation	Reduced	No	2
Murray, 1971 [37]	Observation	Increased	No	3
Messineo, 2017 [35]	PSG	Reduced	No	4
Scott, 1972 [42]	PSG	Varies	Varies	5
Stanchina, 2005 [45]	PSG	Reduced	Yes	6
Suzuki, 1991 [46]	PSG	Reduced	No	7
Terzano, 1990 [48]	PSG	Increased	Yes	8
Borkowski, 2001 [13]	Sleep Diary	Reduced	N/A	9
Cautilli, 2005 [23]	Sleep Diary	Reduced	N/A	10
Forquer, 2005 [27]	Sleep Diary	Reduced	N/A	11
Forquer, 2007 [28]	Sleep Diary	Reduced	N/A	12
Knight, 2014 [33]	Sleep Diary	Reduced	N/A	13
Montgomery-Downs [36]	Sleep Diary	Reduced	Yes	1
Rosalez [41]	Sleep Diary	Reduced	N/A	14
Farrehi [26]	Questionnaire	Reduced	No	15
Gragert [30]	Questionnaire	Reduced	Yes	2
Lee [34]	Questionnaire	No effect	No	16
Williamson [54]	Questionnaire	Reduced	Yes	17
Sleep Quality				
Lee, 2011 [34]	Actigraphy	Varies	Varies	1
Montgomery–Downs, 2010 [36]	Actigraphy	No effect	No	2
Rocknathan, 2017 [40]	Actigraphy	N/A	N/A	3
Gragert, 1990 [30]	Observation	Increased	Yes	4
Rocknathan, 2017 [40]	EEG	N/A	N/A	3
Messineo, 2017 [35]	PSG	No effect	No	5
Terzano, 1988 [47]	PSG	Reduced	Yes	6
Terzano, 1990 [48]	PSG	Reduced	Yes	7
Terzano, 1993 [49]	PSG	Reduced	Yes	8
Terzano, 1995 [50]	PSG	Reduced	N/A	9
Farokhnezhad, 2016 [25]	Questionnaire	Increased	See notes	10
Gragert, 1990 [30]	Questionnaire	Increased	Yes	4
Handscomb, 2006 [31]	Questionnaire	Reduced	Varies	11
Messineo, 2017 [35]	Questionnaire	No effect	No	5
Montgomery–Downs, 2010 [36]	Questionnaire	Increased	No	2
Terzano, 1988 [47]	Questionnaire	Reduced	N/A	6
Terzano, 1990 [48]	Questionnaire	Reduced	Yes	7
Terzano, 1993 [49]	Questionnaire	Reduced	Yes	8
Terzano, 1995 [50]	Questionnaire	N/A	N/A	9
Williamson, 1992 [54]	Questionnaire	Increased	Yes	12
Zhou, 2012 [57]	Questionnaire	Increased	N/A	13
Sleep Duration				
Lee, 2011 [34]	Actigraphy	Varies	Varies	1
Montgomery–Downs, 2010 [36]	Actigraphy	Reduced	No	2
Rocknathan, 2017 [40]	Actigraphy	N/A	N/A	3
Ashton, 1971 [21]	Observation	No effect	No	4
Brackbill, 1973 [22]	Observation	Increased	Yes	5
Murray, 1971 [37]	Observation	No effect	No	6
Gragert, 1990 [30]	Observation	Increased	N/A	7
Rocknathan, 2017 [40]	EEG	N/A	N/A	3
Messineo, 2017 [35]	PSG	Reduced	No	8
Scott, 1972 [42]	PSG	No effect	No	9
Stanchina, 2005 [45]	PSG	No effect	No	10
Terzano, 1990 [48]	PSG	Reduced	Yes	11
Terzano, 1993 [49]	PSG	Reduced	Yes	12
Terzano, 1995 [50]	PSG	Reduced	No	13
Rocknathan, 2017 [40]	Sleep Diary	N/A	N/A	3
Sezici, 2018 [43]	Sleep Diary	Increased	Yes	14
Farokhnezhad, 2016 [25]	Questionnaire	Increased	See notes	15
Wake Duration				
Lee, 2011 [34]	Actigraphy	Varies	Varies	1
Montgomery–Downs, 2017 [36]	Actigraphy	No effect	No	2
Rocknathan, 1971 [40]	Actigraphy	N/A	N/A	3
Ashton, 1971 [21]	Observation	No effect	No	4
Brackbill, 1973 [22]	Observation	Reduced	Varies	5
Murray, 1971 [37]	Observation	Reduced	No	6
Young, 1988 [56]	Observation	No effect	No	7
Rocknathan, 2017 [40]	EEG	N/A	N/A	4
Zhou, 2012 [57]	EEG	Reduced	N/A	8
Messineo, 2017 [35]	PSG	Reduced	No	9
Scott, 1972 [42]	PSG	No effect	No	10
Suzuki, 1991 [46]	PSG	No effect	No	11
Terzano, 1990 [48]	PSG	Increased	Yes	12
Terzano, 1995 [49]	PSG	Increased	Yes	13
Terzano, 1993 [50]	PSG	Increased	Yes	14
Montgomery–Downs, 2010 [36]	Sleep Diary	Reduced	No	2

For each sleep outcome, studies are listed multiple times if multiple measures or outcomes were reported.
Abbreviations: electrocardiogram (EKG), electroencephalography (EEG), no conclusions drawn on effect or no statistical analyses conducted (N/A) polysomnography (PSG).
Effect: The effect of continuous noise or the intervention on the outcome metric.
Significant: The effect of continuous noise or intervention is or is not significant.
Varies: Inconsistent results across samples in experiment or sleep outcomes.
If Table 1 included one sample, the results shown are within-subject comparisons.
If Table 2 included two samples, the results shown are between-subject comparisons.

visual analog scales or the Pittsburgh Sleep Quality Index or Richards-Campbell Sleep Questionnaire.

Continuous noise improved sleep quality among already hospitalized patients potentially by reducing sleep onset latency and/or sleep fragmentation [30,54]. Broadcasting continuous noise for 1 h during three nights in the noisy hours of a hospital ward also mitigated declines in sleep quality after hospitalization [25]. Handscomb [31] found that short-term use (three-14 weeks) of WNMs significantly improved sleep quality among tinnitus patients in the home environment. However, secondary analyses revealed that these effects did not significantly differ as a function of whether the device was regularly used or never or occasionally used.

Lee and Gay [34] found that the multi-component intervention introduced during the third trimester significantly improved sleep quality among first time mothers with low but not high socioeconomic status. It remains unclear which experimental intervention improved sleep quality in one sample but not the other. Given that the intervention did not reduce the sleep fragmentation measure, the improved sleep quality does not appear to be attributable to reducing (at least self-reported) sleep disturbances.

Terzano and colleagues [47–49] found that continuous noise degraded sleep quality as assessed by an increase in the CAP rate among healthy young adults. The authors concluded that this was indicative of NREM sleep stability and continuity that was not detected by more traditional polysomnography parameters. Corroborating the finding, Terzano and colleagues [48,49] found that continuous noise reduced subjective sleep quality. In the remaining studies, continuous noise did not affect sleep quality, the effects were not statistically examined, or conclusions were not drawn due to inadequate data.

Table 3
GRADE evidence profile table.

Certainty Assessment and Quality of Evidence[a]						
No of studies	Study design	Risk of bias	Inconsistent	Indirectness	Imprecision	Quality of Evidence
Sleep onset latency						
21	Varies	Serious	Serious	Not Serious	Serious	Very Low
Sleep Fragmentation						
19	Varies	Serious	Very Serious	Not Serious	Serious	Very Low
Sleep Quality						
14	Varies	Serious	Very Serious	Not Serious	Serious	Very Low
Sleep & Wake Duration						
19	Varies	Serious	Serious	Not Serious	Serious	Very Low

[a] Quality of evidence started at moderate due to having a combination of randomized controlled trial studies and observational studies. For each outcome, quality of evidence was downgraded one level each for risk of bias (see LOW results), inconsistency (heterogeneity in samples, sleep outcomes, noise characteristics, use of multi-component interventions, and results) and imprecision (studies had small sample sizes and statistical analyses were frequently not conducted). No downgrades to quality of evidence were given for indirectness or publication bias. No upgrades to quality of evidence were given for magnitude of effect, confounding adjustments, or evidence for dose response gradient.

Sleep & wake duration

Eighteen studies (47.4%) included sleep or wake duration as outcomes (see Tables 1–2). Sleep duration was assessed using total sleep time but some studies also included time-in-bed, sleep period time, or duration of sleep bouts as outcomes. Wake duration was assessed using wake after sleep onset or hours or percentage of time awake. Five observation studies stratified sleep into states such as regular and irregular sleep, and alert and crying. In an observation study with Alzheimer's patients, Young and colleagues [56] constituted awake and restless states as nocturnal wandering behavior (i.e., a tendency to wander at night).

The sleep and wake duration results were often consistent with the sleep quality results. That is, sleep quality was positively associated with total sleep time and/or negatively associated with wake after sleep onset. If continuous noise did not affect sleep quality then it also often did not affect total sleep time or wake after sleep onset. Terzano and colleagues [48,49], for example, found that continuous noise reduced sleep quality and total sleep time and increased wake after sleep onset. Lee and Gay [34] found that the multi-component intervention that increased sleep quality and total sleep time and reduced wake after sleep onset in one of two cohorts of first time mothers, with results only reaching significance at three-months postpartum. Farokhnezhad [25] found that broadcasting continuous noise for 1 h for three nights during the noisy hours in a hospital ward mitigated declines in total sleep time as well as sleep quality. Brackbill [22] found that 2 h of continuous auditory, visual, proprioceptive-tactile, and temperature stimulation significantly increased the time infants spent in quiet sleep (i.e., general muscular relaxation) and active sleep states (i.e., relatively frequent diffuse movements) and reduced time spent in a crying state (i.e., considerable gross motor activity and crying). The stimulation did not, however, significantly affect time spent in a drowsy state (i.e., a relaxed state and falling asleep) or quiet awake state (i.e., little gross motor activity with some movement of extremities and face) [59].

Stanchina and colleagues [45] found that continuous noise decreased nighttime arousals and masked the recorded ICU sounds. This was not accompanied by a change in total sleep time but it did affect sleep architecture. Relative to baseline, the recorded ICU sounds increased arousals and accordingly increased stage one and stage two sleep and decreased stage three and stage four sleep. Continuous noise mitigated these changes in sleep architecture. Similar findings were reported by Scott [42] but were not corroborated by Suzuki and colleagues [46] or Messineo and colleagues [35]. Terzano and colleagues [48] found nearly opposite findings with an increase in stage shifts and time awake, a decrease in total sleep time and stage 4 sleep, and no significant changes stage 1 sleep.

Risk of bias within studies

Serious risks of bias were detected using the LOW (see supplemental materials). The studies frequently included small sample sizes, which may have contributed to non-significant results. Statistical analyses were frequently not conducted. The effects of continuous noise on sleep were often inconclusive due to confounding factors such as multi-component interventions or the control group receiving an alternative intervention.

Strength of evidence across studies

The quality of evidence on the effects of continuous noise on sleep onset latency, sleep fragmentation, sleep quality, and sleep and wake duration was very low for each outcome using the GRADE assessment (see Table 3).

Discussion

Conventional wisdom contends that continuous noise, such as so-called “white noise machines”, may improve sleep. After systematically reviewing published scientific literature, we conclude that the quality of evidence supporting this assertion is very low. Continuous noise tended to reduce sleep onset latency and sleep fragmentation; however, the effects were either not significant or not statistically analyzed. The lack of effect was likely partly driven by small sample sizes. Across conditions, 18.4% and 36.8% of the studies included less than or equal to 5 subjects and 10 subjects, respectively. The fact that continuous noise tended to reduce sleep onset latency and sleep fragmentation indicates that continuous noise may improve or at least not harm sleep but the quality of evidence is currently very low.

There was some evidence that continuous noise reduced sleep onset latency in the observation studies, where parents or study investigators reported on the sleep of their child or patient, respectively. In the study by Gragert [30], the study investigators' observation that patients fell asleep over an hour faster with continuous noise was corroborated by significant improvements in self-reported sleep onset latency. Continuous noise also helped reduce problems getting to sleep among patients with severe tinnitus [51].

There was also some evidence that continuous noise reduced sleep fragmentation resulting from hospital noise. For example, Stanchina and colleagues [45] found that continuous noise reduced sleep fragmentation among healthy adults exposed to recorded intensive care unit noise, and concluded that continuous noise increased arousal thresholds by reducing the difference between background noise and peak noise. While this conclusion is consistent with the theory that continuous noise improves sleep by masking other sounds and increasing the threshold for hearing a sound, the literature reviewed does not provide enough evidence to support or refute any of the theories.

Contrary to the theories on the sleep-promoting effects of continuous noise, introducing a continuous noise into the bedroom environment could potentially disrupt sleep or induce hearing loss or other health consequences. The studies by Terzano and colleagues [47–50] provide some evidence that continuous noise disrupts sleep. Interestingly, the acoustic perturbation of continuous noise on sleep fragmentation, sleep quality, and sleep duration increased with increases in the intensity of the sound pressure [48]. Of note, the sleep quality measure (i.e., CAP rate) used in the studies was developed by the research group and it was not used in the other studies [58]. This could account for discrepancies on the effects of continuous noise on sleep quality but not sleep fragmentation and sleep duration, which were assessed using standard outcomes.

The finding that continuous noise often did not help or disrupt sleep could be due to its short-term use. Under the stimulus control theory, this short-term use could have been insufficient for individuals to associate continuous noise as a cue for sleep. It is also possible that individuals would habituate with long-term use, therefore lowering the efficacy of the continuous noise. Another possibility for the lack of observed effects is that WNMs may be most effective on only certain individuals of a population not captured by the current studies. Finally, the studies are limited by the fact that study participants cannot be blinded to the continuous noise intervention, which is particularly relevant for studies that rely on self-report.

Across studies, noise levels in the experimental condition varied between 20 and 93 dB. This range corresponds to over 4000 times the sound pressure and approximately 17 million times the acoustic energy since a 6 dB increase in sound pressure level corresponds to a doubling of sound pressure in Pascals and a quadrupling of the acoustic energy. Furthermore, the lowest noise level (20 dB, approximate level of a whisper) is perceived as over 130 times quieter than the highest level (93 dB, approximate level of a motorcycle engine) since perceived loudness of a sound approximately doubles with a 10 dB increase.

While Terzano and colleagues [48] found a dose–response relationship between sound pressure levels and sleep outcomes, this dose–response relationship was not evident across studies. There was no clear relationship between noise characteristics and the effects on sleep onset latency, sleep fragmentation, sleep quality, and sleep and wake duration. A limitation of over half of the studies was that the frequency weighting of the noise levels was not reported, and it was not possible to compare differentially-weighted levels since the overall level is highly dependent on the frequency spectrum of the noise (see Fig. 3). Similarly, the term "white noise" was frequently used to describe noise that was not truly white noise (see Fig. 1). Despite the studies using continuous noise, it was not possible to determine the precise nature of the noise unless the noise characteristics were explicitly defined.

There are several limitations that should be noted with regards to this systematic review. This systematic review only included articles that were written in or translated into English, and there may be additional articles written in other languages that could have contributed to the knowledge base. Despite including thirty-eight articles, a systematic review was opted for over a meta-analysis due to heterogeneity in research methods, including the population of interest, study design, noise characteristics, sleep measurement methodology, sleep outcomes, and statistical analyses, if any. As such, effect size calculations could not be conducted. Finally, there were few randomized controlled trials and we opted to include all studies examining the effects of continuous noise on sleep rather than limiting the analyses to randomized controlled trials.

There are also several strengths to this systematic review. Standard protocols were followed to conduct the systematic review (i.e., the PRISMA) and assess the quality of evidence (i.e., the GRADE criteria), and all evidence was reviewed independently by multiple investigators. The outcomes included sleep onset latency, sleep fragmentation, sleep quality, and sleep and wake duration, and thus multiple dimensions of the sleep promoting or sleep disrupting effects of continuous noise were assessed. The inclusion criteria were broad in terms of study population so the findings are not limited to a single subpopulation; however, this consequently introduces heterogeneity into the methods and possibly the results. Authors of the studies were contacted if the weighting used in the study was not specified, and this information was obtained for a couple studies. Finally, this systematic review provides a timely review of the literature given the increasing public awareness of the importance of sleep health and the continued widespread use of sound machines and applications.

The results from this systematic review suggest that additional research is needed to elucidate the effects of continuous noise on sleep among human subjects. The very low quality and contradictory nature of the evidence is in stark contrast to the widespread use of WNMs. More rigorous research with objective sleep measures and detailed noise descriptions, including sound pressure level, frequency weighting, noise location, noise type (e.g., pink, white, broadband), background noise, exposure-response relationships, and spectral content is needed before recommendations for the use of WNMs are justifiable, particularly considering that continuous noise may negatively affect sleep and hearing.

Practice Points

1. A quiet, dark, and cool bedroom environment is a cornerstone of sleep hygiene recommendations and important for getting a good night's sleep.
2. White noise machines are purported to mask disruptive noises and improve sleep quality; however, the efficacy of continuous noise to improve sleep measures remains unclear.
3. The results from this systematic review indicate that quality of evidence of continuous noise to improve sleep onset latency, sleep fragmentation, sleep quality, and sleep and wake duration is very low.

Research Agenda

1. There is a need for large-scale research studies aimed at evaluating objective and subjective changes in sleep with the introduction of continuous white noise. These studies should better describe the acoustic characteristics of both the background and continuous noise.
2. Studies on examining long-term use and exposure-response relationships are also needed.

Conflicts of interest

The authors do not have any conflicts of interest to disclose.

Acknowledgements

We thank the authors that provided us with information on the frequency weighting used by the sound level meters in their study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.smrv.2020.101385.

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