Sleep Medicine Reviews (2007) 11, 135–142

SLEEP MEDICINE reviews

www.elsevier.com/locate/smrv

CLINICAL REVIEW

Environmental noise, sleep and health

Alain Muzet*

FORENAP, BP 27, Rouffach, France

KEYWORDS
Noise;
Sleep disturbance;
Subjective evaluation;
Health effects;
Habituation;
Age

Summary Unlike other physical ambient factors (i.e. electromagnetic fields or air pollutants), noise is perceived by a specific system (auditory system) in humans. It is therefore a phenomenon that is sensed and evaluated by everybody, and this is why exposure to noise is one of the most, if not the most, frequent complaints of populations living in large cities. In these areas and their surroundings, the sources of noise most frequently cited are traffic, followed by neighbourhood noises and aircraft noises. Sleep is a physiological state that needs its integrity to allow the living organism to recuperate normally. It seems to be sensitive to environmental factors that can interrupt it or reduce its amount. Ambient noise, for example, is external stimuli that are still processed by the sleeper sensory functions, despite a non-conscious perception of their presence. Over the past 30 years, research into environmental noise and sleep has focused on different situations and environments, and therefore the findings are variable. However, it still seems necessary for some fundamental questions to be answered on whether environmental noise has long-term detrimental effects on health and quality of life and, if so, what these effects are for night-time, noise-exposed populations.

Sound and noise

Sound is produced by any mechanical movement and is propagated as a motion wave through the air or any other material. Therefore, sound is defined by its mechanical energy and is measured in energy-related units. Sound pressure proportional to the square of sound intensity (W/m^2) is expressed in Pascal units (Pa), whereas sound pressure level is expressed in decibel units (dB) on a logarithmic scale, owing to the wide range covered.

Sound evokes physiological signals in the auditory system constituted by the ear and the auditory pathways. However, some sounds do not evoke those signals as they are out of the auditory perception range in humans, which theoretically ranges from 20 to 20,000 Hz.

Noise is generally defined as an unwanted sound or set of sounds. This definition means that it is not possible to classify sounds as noise on the unique basis of their physical characteristics. The general agreement is that noise is an audible acoustic phenomenon that adversely affects, or may affect, people. The effects of noise can be appreciated physiologically but also psychologically (annoyance and disturbed well-being).

*Tel.: +33 3 89787370; fax: +33 3 89787371.
E-mail address: alain.muzet@forenap.com.

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doi:10.1016/j.smrv.2006.09.001

Noise in the environment

Noise is a phenomenon that affects everybody. We are constantly exposed to noise during our everyday life. Within our environment, there are different sources of noise, but they generally depend on our activity, location, and the time of day.

Transportation noise represents a large majority of external noise affecting people in large cities and their surroundings. Road traffic noise is mostly noise generated by the engine of the vehicle, but noise produced by frictional contact between the vehicle and the air, as between tyres and the road surface, exceeds engine noise at speeds higher than 50 km/h for passenger cars and at speeds higher than 80 km/h for lorries. Railway noise mainly depends on the speed of the train and the quality of the track. High-speed trains, for instance, might produce high-frequency noise, which is fairly similar to those generated by jet aircrafts. The expected development of this high-speed freight transport system in the next few years should be regarded as potentially disturbing for people living alongside the rail tracks, especially at night. Air traffic noise has been given much research attention during the past 30 years. Noise from a single aircraft, however, has considerably diminished during this period, as the concept of engines and flying machines has changed. However, increasing volume of traffic, and specifically night-time traffic, has often created conflict between populations living around large airports and the airport authorities.

Industrial plants can also be a source of excessive noise for the surroundings. This type of noice can be complex in nature, owing to the wide variety of sources. It can be spontaneous or more or less continuous, with large variations in intensity. Low-frequency noises are not so well attenuated by surrounding structures, and they can be transmitted across large distances. Building construction and ground work (e.g. hammering, crane, or heavy trucks) can generate high noise emissions. Military activities, although generally limited to specific areas, may also cause large noise disturbances for the surrounding populations.

Inside buildings, several different types of noises can be found: mechanical devices (e.g. lift, ventilation, pumps, water pipes) or domestic noises (e.g. neighbour's voices, Hi Fi, TV set, pets, and musical instruments). Ventilation noise can be quite disturbing in residential areas because of its low-frequency characteristics, even at low A-weighted sound pressure levels.[1] Domestic noises are among the most frequently reported causes of annoyance and the most difficult to characterize and quantify.[2] This is mainly due to the general attitude of the exposed people towards the source of noise and who is responsible for it. Neighbourhood noises (e.g. voices, music or footsteps) have high information content, which may catch the attention of the listener, independent of their intensity. Thus, independent of the noise exposure characteristics, the psychological dimension of the expressed annoyance is highly related to the specific relationship that exists between the noise producer and the noise receiver (''the bark of your neighbour's dog is much louder than the bark of your dog''). Therefore, in the domestic setting, the physical characteristics of the noise are often less important than the resultant attitude towards the source of the noise.[3]

Noise from leisure activities is clearly increasing with the invasion of more powered machines on the ground as well as in air and water (e.g. off-road vehicles, motorboats, and sporting airplanes). They are often limited to more or less specific areas, but they tend to increase at the periphery of large cities. Outdoor shooting activities, as well as outdoor concerts, have to be avoided in residential areas, but less noisy activities are often programmed almost everywhere and are, in addition, often accompanied by increased motor traffic.

The exposure to noise

As discussed previously, complaints about global noise exposure are one of the most, if not the most, frequent complaints among populations living in large cities.[4] Surveys show that frequency of complaints from noise increases with the size of cities, and that exposure to noise is inversely related to family income, with those on lower levels of income being the most exposed to ambient noise.[2] The most frequently cited sources are traffic noises, followed by noises from the neighbourhood and then aircraft noises.

Ten years ago in France, the number of people living in a ''noisy environment'' was estimated to be 10% of the total population or 6 million individuals, comprising 2 million (including 450,000 children) exposed to high levels of noise above 70 dB Leq 8h–20h (Leq or equivalent noise level: constant noise level having an equivalent energy to the total energy of the actual noises occurring between 08:00 and 20:00).[5] Unfortunately, there is no reason to believe that this picture has much improved, and these days the numbers are certainly higher. However, the extent of the noise problem is large, and the case given

above can be applied to many more industrialized countries. Thus, annoyance to community noise is widespread among citizens in the European Union, and the number of people exposed to moderately high levels (55–65 dB Leq) still increases in those countries. This is mainly due to the increasing sources of noise and their wider dispersion, along with greater individual mobility and growing leisure activities.

Sleep disturbance due to noise

Sleep disturbance is part of the extra-auditory effects of noise (Fig. 1). The input to the auditory area of the brain through the auditory pathways is prolonged by inputs reaching both the brain cortical area and the descending pathways of the autonomic functions. Thus, the sleeping body still responds to stimuli coming from the environment, although the noise sensitivity of the sleeper depends on several factors. Some of these factors are noise dependent, such as the type of noise (e.g. continuous, intermittent, impulsive), noise intensity, noise frequency, noise spectrum, noise interval (e.g. duration, regularity, expected), noise signification and the difference between the background noise level and the maximum amplitude of the occurring noise stimulus. Other factors are related to the sleeper, such as age, sex, personality characteristics and self-estimated sensitivity to noise.

The effects of noise on sleep can be immediate or secondary to the noise exposure. The first category corresponds to responses occurring simultaneously or immediately after the noise emission, whereas the latter corresponds to effects visible the next day or after a few days.

Immediate effects: objective measures of sleep disturbance

Sleep disturbance may be quantified by number and duration of nocturnal awakenings, number of sleep stage changes, and modifications in their amount. Proper rhythms of particular sleep stages (i.e. slow wave sleep [SWS] or stages 3 and 4, and rapid eye movement [REM] sleep [Fig. 2]), also characterize sleep disturbance, together with modifications in the autonomic functions (heart rate, blood pressure, vasoconstriction and respiratory rate).

Shortening of the sleep period

Total sleep time can be reduced by both longer time to fall asleep and premature final awakening. It has been reported that intermittent noises with peak noise levels of 45 dB(A) and above, can increase the time to fall asleep by a few minutes to 20 min.[6] On the other hand, sleep pressure is significantly reduced after the first 5 h. Therefore, in the morning hours, noise events can more easily awake and prevent the sleeper of going back to sleep. The main problem, however, is to determine whether

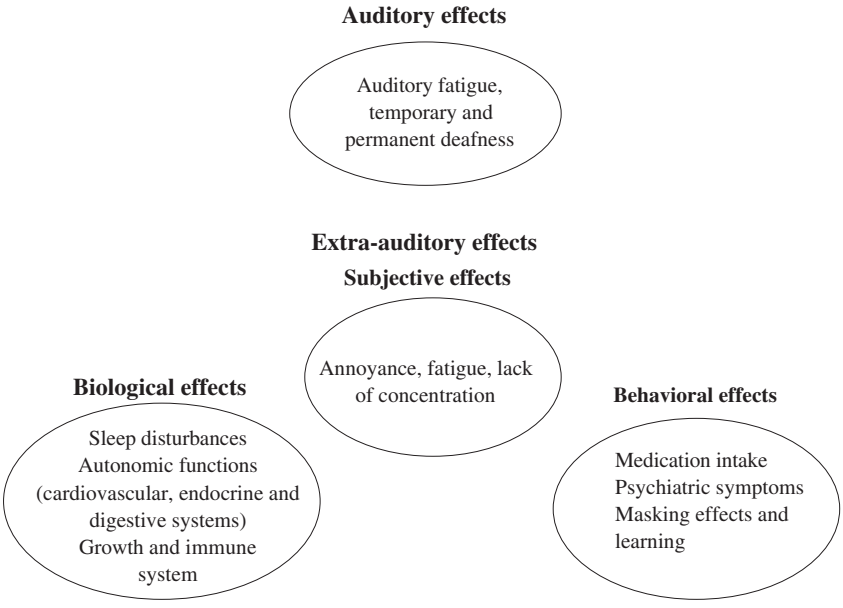

Figure 1 Auditory and extra-auditory effects of noise.

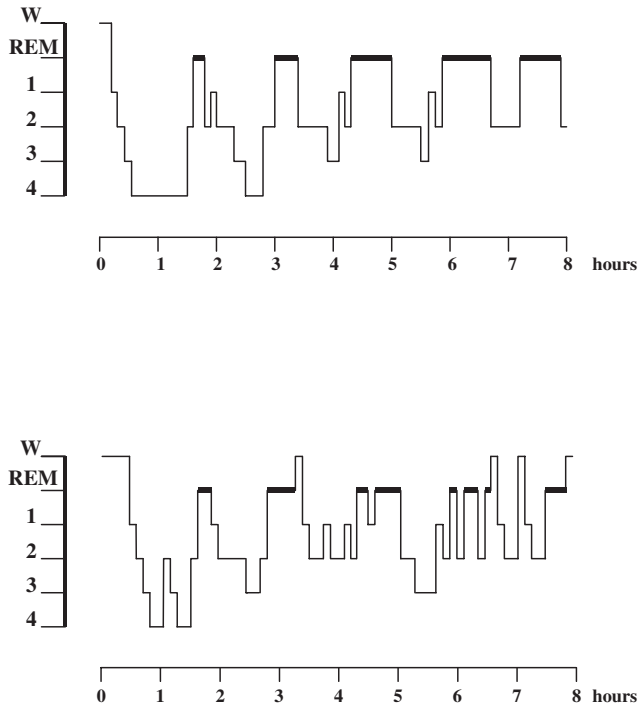

Figure 2 Hypnograms of a young adult. Top: during non-disturbed sleep. Sleep onset occurs within 10 min after light out time (0). Sleep begins by NREM sleep stages and the first REM episode occurs some 90 min after sleep onset. SWS (stages 3 and 4) occurs mainly during the first 3 h of the night. REM sleep episodes appear at very regular intervals. No awakening is seen during the entire night. Bottom: during a noise-disturbed night. Sleep onset is slightly delayed. The first episode of stage 4 is partly interrupted. A significant amount of SWS does occur during the fifth hour (possibly as a compensatory mechanism of the disturbed first episode). REM sleep still shows clear rhythmic occurrence but some of the episodes are fragmented. Significant awakenings occur throughout the sleep process. Sleep efficiency is reduced.

a significant part of sleep can be chronically reduced with no detrimental effect in the long term.

Sleep awakenings

It seems obvious that noise occurring during sleep may cause awakenings. The awakening threshold observed with noise (the sleeper is asked to push a button when awake) depends on several factors. In the sleeper's current stage of sleep, the threshold is particularly high in deep slow wave sleep (stages 3 and 4), whereas it is much lower in shallower sleep stages (stages 1 and 2).[7] The awakening threshold also depends on physical characteristics of the noisy environment (intermittent or sharp rising noise occurring above a low background noise will be particularly disturbing), as well as noise signification. Thus, whispering the sleeper's name can awake the person more easily than a much louder but neutral acoustic stimulus.[8] Similarly, and with a similar intensity, the noise of an alarm will awaken the sleeper more easily than a noise without any particular signification.

Sleep stage modifications

If nocturnal awakenings can be provoked for peak noise level of 55 dB(A) and above, disturbance of normal sleep sequence can be observed for peak noise levels between 45 and 55 dB(A). In order to protect noise-sensitive people, The World Health Organization recommended a maximal level (LA-max) inside the bedroom at night of 45 dB, whereas, for the same period, the mean recommended level (integrated noise level over the 8 nocturnal hours: Lnight) was of 30 dB.[9]

SWS and REM sleep are both considered to be important stages of sleep, which should be well protected. SWS seems to be an energy restoration state of the sleeping body, whereas REM sleep seems to be more related to mental and memory processes. Carter[10] reported that SWS could be reduced in young sleepers exposed to intermittent noises. We previously reported that REM sleep rhythmicity could also be affected by environmental noise exposure.[11] It is a common observation in all noise-disturbed sleep studies to see an increase in sleep stage changes resulting in a reduced amount of SWS and REM sleep to the benefit of

shallower sleep stages. This instability of the sleep process might be detrimental if it becomes chronic. Its picture is close to that observed in chronic insomniacs, and exploring the long-term evolution of such sleep disturbance could be important.

Autonomic responses

Awakenings and sleep-stage modifications are not the only possible acute effects of noise on the sleep process itself. The limit values given above do not mean that for lower noise levels there are no more effects on the sleeper. Autonomic responses, such as heart rate changes and vasoconstrictions, can be obtained for much lower peak noise intensities, indicating that the sleeping body still perceives the external stimuli even if there is no consciousness or memory about these events the next day.[7] Although these effects are considered to be minimal, they have been found not to habituate over long exposure times compared with clear subjective habituation over successive noise-exposed nights.[12,13] These autonomic responses represent reflex responses of the sleeping body to the external stimuli, which can already be observed at quite a low intensity. The health effects of long-term repetition of such responses should be discussed, especially in the case of multi-exposure (e.g. air and surface traffic). In this situation, there could be a cumulative effect of these cardio-vascular responses over a few thousands stimuli per night.

Secondary effects of the sleep disturbance due to noise

The secondary effects of night-time noise exposure can be separated into subjective reports of sleep disturbances and objective effects on daytime functioning.

Subjective evaluation of sleep disturbance

Objective recordings of sleep disturbance data are too costly and too difficult to use with large samples of the population or when funding is limited. Next-day subjective evaluation of sleep quality is a much easier and less costly way of collecting data, especially in the field. Sleep disturbance *per se* can be assessed from complaints about bad sleep quality, delayed sleep onset, nocturnal awakenings, and early morning waking up. These sleep disturbances are often accompanied by impaired quality of the subsequent daytime period with increased tiredness, daytime sleepiness and need for compensatory resting periods.[2]

However, the actual value of subjective complaints might be quite different from assessments based on instrumental measures. In fact, many factors influence people's subjective evaluations of their own sleep quality. Several studies show that subjective self-reports on sleep quality or on nocturnal awakenings do not correlate well with more objective measures of sleep disturbance.[14] When the number of noise events increases, the number of sleep modifications or awakenings also increases, although not proportionally. As indicated by Porter et al.[15] noise heard at night will be more intrusive and noticeable than during the day. This is caused by reduced outside and inside background noises at night and to the circadian fluctuation of biological rhythms. The night-time period may also be a time of higher noise sensitivity, especially if awakenings related to aircrafts flying over occur. Therefore, use of self-reports of movement, awakenings, or other sleep-related effects, needs serious reconsideration because of their questionable validity.

However, if the number of noise events is important and the noise level is high, nocturnal awakening can be excessively prolonged and even constitute a premature final awakening of the night. Sleep disturbance occurring during the early part of the night and during the time just preceding usual awakening seems to be most annoying.[6,16] In this case, sleep disturbances will lead to excessive daytime fatigue, often accompanied by daytime sleepiness, with its specific effects being low work capacity and increased accident rate.

Fear of living under aircraft routes is often a major reason of protesting against aircraft noise even if the measured noise levels are relatively low. This largely accounts for the difficulty in trying to find a clear relationship between subjective complaints and actual noise exposure.

Other secondary effects

In addition to subjective evaluations of sleep quality, after-effects of nocturnal noise exposure can be measured the following morning by objective biochemical data (i.e. increase in levels of stress hormones, including noradrenalin, adrenalin and cortisol),[10,17,18] or by cognitive performance deterioration during the next day.[19,20]

Physiological sensitivity to noise

The noise physiological sensitivity depends also on the age of the sleeper. Although electroencephalogram (EEG) modifications and awakening thresholds are, on average, 10 dB(A) higher in children than in adults, their cardiovascular sensitivity to noise is similar to, if not higher than, older people.[21] Elderly people complain much more than younger adults about environmental noise. However, their spontaneous awakenings during sleep are also much more numerous. Therefore, it is difficult to conclude if elderly people are more sensitive to noise or if they hear noise because they are often awake during the night. This natural fragmentation of their night sleep tends also to lengthen their return to the sleeping state, and this accounts for a significant part in their subjective complaints. The main question about possible sensitive groups remains almost entirely unanswered. Most of the studies (in laboratories as well as in the home) have been carried out on groups of ''normal'' people or, at least, populations where some pathologies have been systematically excluded.

The particular case of shift workers

The sleep of shift workers is often disturbed by combined influences of ambient factors (noise is one of them) and chronobiological factors (sleeping at an unusual time of the day). Thus, noise was considered as the first cause of sleep interruptions in a group of female shift workers.[22] It is also considered a major cause of sleep shortening during daytime.[23] Some investigators comparing daytime to night-time sleep disturbance due to noise in shift workers, have found that the percentage of noise-induced EEG effects was significantly higher during the day than during the night-time REM sleep.[24] These investigators also stated that the inversion of the sleep–wake cycle did not markedly influence the average cardiovascular reactivity to noise, and they concluded that daytime sleep disturbance by noise was as important and harmful as night-time disturbance. Carter et al.[25] underlined the effects of noise on the cardiovascular side and, particularly, the modifications in blood pressure due to suddenly occurring noises.

Possible health effects of noise-disturbed sleep

From a public health perspective, it is necessary to be able to link sleep disturbance from noise exposure with long-term health effects. Of course, these effects depend on the magnitude and the repetition of sleep disturbance. To be awakened when engaged in a quiet and comfortable universe full of sweet dreams is, *per se*, a real aggression that only few sleepers may appreciate. However, it is much more through the reduction of daytime quality of life that sleep disturbance can be evaluated. Chronic partial sleep deprivation induces marked tiredness, increases a low vigilance state, and reduces both daytime performance and the overall quality of life.[26] Excessive daytime fatigue accompanied by sleepiness, deterioration of normal behaviour, expression of anger, lack of concentration and reduced work ability are often associated with chronic sleep deprivation. In this case, the need for additional resting period during the daytime is not always satisfied. In fact, the subtle equilibrium between waking and sleeping states is deteriorated to the detriment of the quality of both states.

More generally, some health effects, such as increased prescription of drugs around major airports[27] or increased rate of psychiatric hospital admission[28] could also be related to night-time noise exposure. However, many confounding factors cannot be eliminated in these epidemiological studies and, therefore, it remains difficult to confirm such results. The perception by the exposed population of possible factors affecting their health is often reported by the airport services in charge of communication with the public. Most of the complaints refer to sleep disturbance, general fatigue and anxiety. Noise is then clearly identified as a factor of stress and stress may be considered as the possible mechanism through which mental and physical health can be affected by noise.[29]

Of particular interest is the possible relationship between noise and the stress responses it produces, as they have the potential to be linked to hypertension, cardiovascular disease and other severe medical problems.[30–37] As mentioned previously, there is also a need to protect sensitive groups and shift workers who sleep during the day.[25]

Conclusion

Sleep is a physiological state that needs its integrity to allow for normal recuperation of the living organism. Its reduction or disruption is detrimental in the long term, as chronic partial sleep deprivation induces marked tiredness, increases low vigilance state and reduces daytime performance

and quality of life. Sleep seems to be fairly sensitive to environmental factors, and, specifically, to ambient noise, as external stimuli are still processed by the sleeper sensory functions, despite a non-conscious perception of their presence.

The large amount of research developed in the laboratory during the past 30 years has produced variable results, and some of them seem quite controversial. In fact, the effects of noise exposure depend on several factors, and the absence of a clear dose–effect relationship is certainly due to the complex interactions of these factors, including the noise characteristics, the individual sensitivity and the context of the explored living environment. However, the amplitude of the subjective complaints about sleep disturbance seems to have been increasing during recent years. Unfortunately, only a few epidemiological studies have considered the possible effect of noise exposure (considered globally), together with other environmental factors, on the health of exposed populations. To our knowledge, no large-scale epidemiological study focusing on the effect of night-time noise exposure on health has yet been undertaken. Therefore, it is necessary to answer some fundamental questions in order to understand the detrimental effects on health and quality of life in the long term, for night-time, noise-exposed populations. Continuous high-level exposure can lead to aggression in a hostile, angry, and helpless population. It is often the population with the least income that suffers the most from noise in general. Also, annoyance due to ambient noise may be often seen as the visible part of a greater problem. Therefore, it should be an everyday concern to protect these populations against this major environmental aggression.

Practice points

Immediate and secondary effects of sleep disturbance due to noise are as follows:

Immediate effects:

- Delayed sleep onset, earlier final awakening or nocturnal awakenings.
- Sleep stage changes or sleep structure changes.
- Arousals and body movements.
- Vegetative or hormonal responses to noise.

Secondary effects:

- Subjective estimation of sleep quality.
- Performance decrement.
- Change in daytime behaviour.

Research agenda

Future research should focus on:

- Long term effects of night-time noise exposure of different populations.
- The study of specific sub-groups that can be considered to be ''at risk'' (e.g. children, elderly people, self-estimated sensitive people, insomniacs, sleep disorder patients, night and shift workers).
- Combined effects of noise exposure and other physical agents or stressors during sleep.

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