Noise and Health - Effects of Low Frequency Noise and Vibrations: Environmental and Occupational Perspectives

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Effects of Low Frequency Noise and Vibrations: Environmental and Occupational Perspectives

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Abbreviations

Lden	day–evening–night average sound level
LpA	A-weighted sound pressure level
LpC	C-weighted sound pressure level
Lpeq	equivalent sound pressure level
LpG	G-weighted sound pressure level
LpLin	Linear sound pressure level
SPL	sound pressure level
TTS	temporary threshold shift
VAD	vibroacoustic disease

Introduction

In nature, sound frequencies below 200 Hz are signals of thunder, volcano eruptions, earthquakes, or storms – events that are likely to induce arousal or fear. In the urban soundscape, low frequencies may originate from amplified music, transportation, or ventilation/compressor units. Human hearing in the low frequency range is, compared to the higher frequencies, less sensitive and has, for many years, led to the misconception that low frequency sounds are also less annoying. Today, it is known that low frequency noise has a great annoyance potential, and that some people seem to react adversely even to levels just above their hearing threshold. Factors inherent in most low frequency noises such as the throbbing characteristics, the intrusion of low frequencies felt when other frequencies in the sound are attenuated, and the vibration sensations sometimes felt contribute probably to annoyance. The risk for adverse effects is of particular concern because of its general presence due to numerous sources, such as an efficient propagation of the noise from the source and poor attenuation efficiency of building structures. The importance of low frequency noise has been acknowledged in the World Health Organization document on community noise, which states that "health effects due to low frequency components in noise are estimated to be more severe than for community noise in general" and that "special attention should be given to sources with low frequency components." At that time, no specific guidelines were suggested to deal with the problem.

In the past decade, low frequency noise has begun to be acknowledged as a public health problem that needs to be attended to, and there are today a number of countries that have specific guidelines for low frequency noise in the community and a few that have specific guidelines for the work environment.

This article focuses on what is known of adverse effects due to community and occupational low frequency noise. Compared to other noise sources, data from low frequency noise are limited, and further studies are clearly needed.

Definition

Low frequencies lack an internationally established definition but usually indicate the frequency range of 20–200 Hz. Although the upper limit for infrasound is 20 Hz, at sufficiently high sound pressure levels (SPLs), certain noises contain in practice both perceivable infrasounds and low frequency sounds. The division between infrasound and low frequency sound should therefore be seen as merely conventional. For both infrasounds and low frequency sounds, their relationship to the perception threshold is of relevance as a first estimate of risk assessment. For the low frequency range, comparisons are made to the standardized normal hearing threshold, whereas for infrasounds, there exists no standardized normal hearing threshold, and assessments have to be made to approximations of present studies of hearing and perception. With respect to effects on humans, many studies have shown that adverse reactions appear when the noise consists of perceivable SPLs in low frequencies that are considerably higher relative to the SPLs above approximately 200 Hz. Thus, in terms of effects, a low frequency noise can be defined as a noise with dominant frequencies in the region of 20–200 Hz and is thus used in this article.

Sources of Low Frequency Noise

Low frequency noise is emitted from a multitude of sources such as large ventilation systems, climate systems, diesel motors (heavy vehicles, diesel locomotives, work machines, generators), aircraft (propeller planes, helicopters, jets), compressors (refrigeration compressors, pressurized air drills), and turbines (Figure 1). Airborne noise of low frequency may also occur as a result of

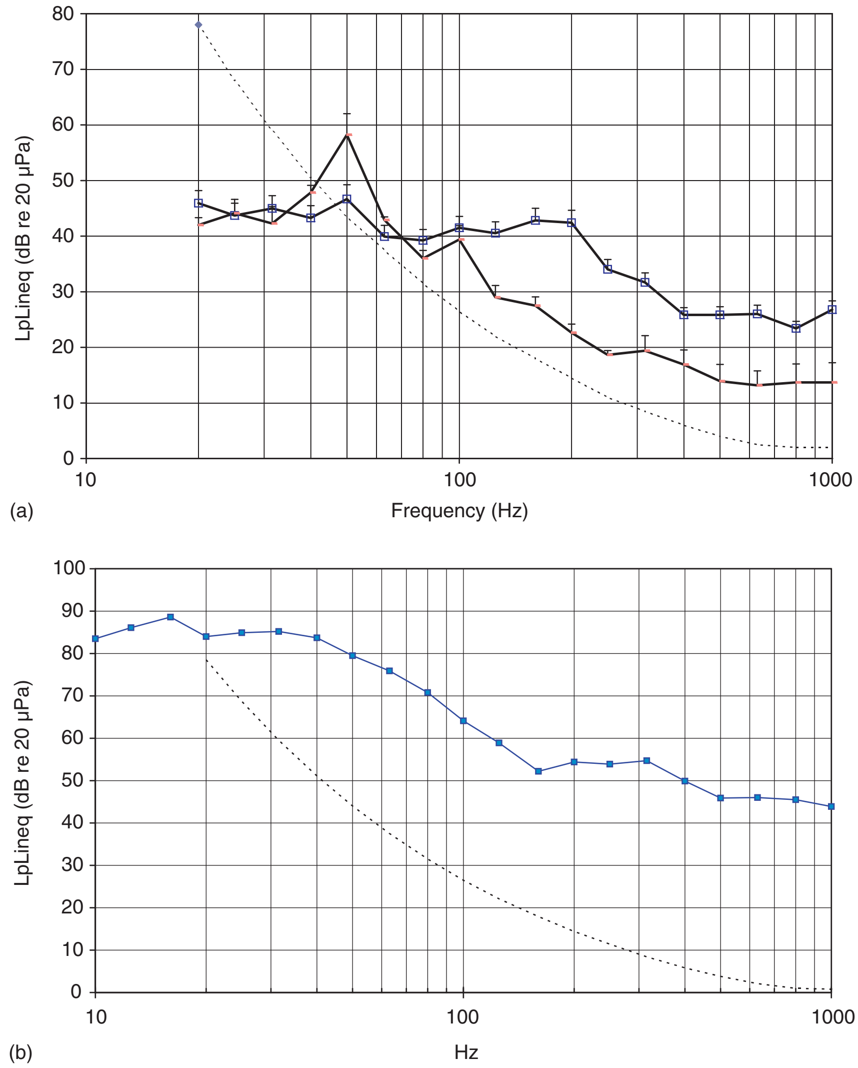

Figure 1 (a) Typical frequency spectra from low frequency indoor ventilation in dwellings in relation to the normal hearing threshold (ISO 389-7 (2005) Acoustics - Reference zero for the calibration of audiometric equipment - Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions. *International Organization for Standardization, Genéve*). Standard deviations represent variations between dwellings with similar ventilation systems. (b) Occupational exposure to jet engines in a test bed. Also shown is the normal hearing threshold (ISO 226 (2003) Acoustics - Normal equal-loudness-level contours. International Organization for standardization,Genéve.).

vibrations in the ground or in building structures. Low frequency noise is also generated when explosives are detonated and in the use of heavy artillery.

Compared to high frequencies, low frequencies propagate for long distances. Low frequencies will also pass with little attenuation through walls and windows. At long distances from the source, or indoors, the noise spectrum will be selectively attenuated, resulting in a spectrum dominated by low frequencies. Examples of situations in which the resulting noise can contain a large portion of low frequencies are interior control rooms, steering compartments, and cockpits and when traditional hearing protection equipment is used (Figure 2).

There are no records on the prevalence of people exposed to or annoyed by low frequency noise. Measures of registered complaints can be seen as an indication, but data are limited to a few countries. From this, a very crude estimate could be that the proportion of complaints on low frequency noise comprises 30–40% of complaints on noise in general. In one study, the median incidence rate, estimated as the number of complaints per 10 000 inhabitants, was 1.1 (25th to 75th percentile; 0.25–2.4) for complaints on low frequency noise, whereas the corresponding rate for noise in general was 3.3 (25th to 75th percentile; 2.5–6.6). However, data also indicate that when low frequency noise occurs as a result of

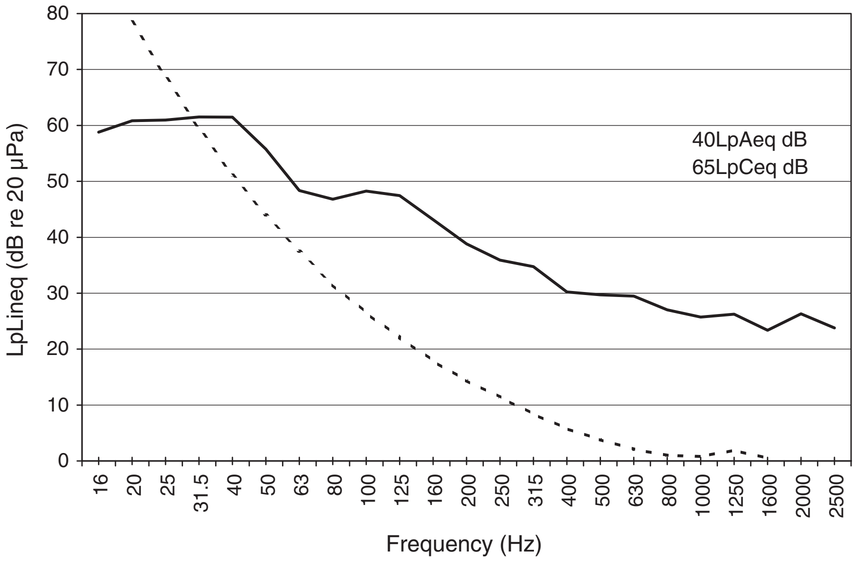

Figure 2 Resulting noise in a control room of a paper mill industry. Also shown is the normal hearing threshold (ISO 389-7:2005).

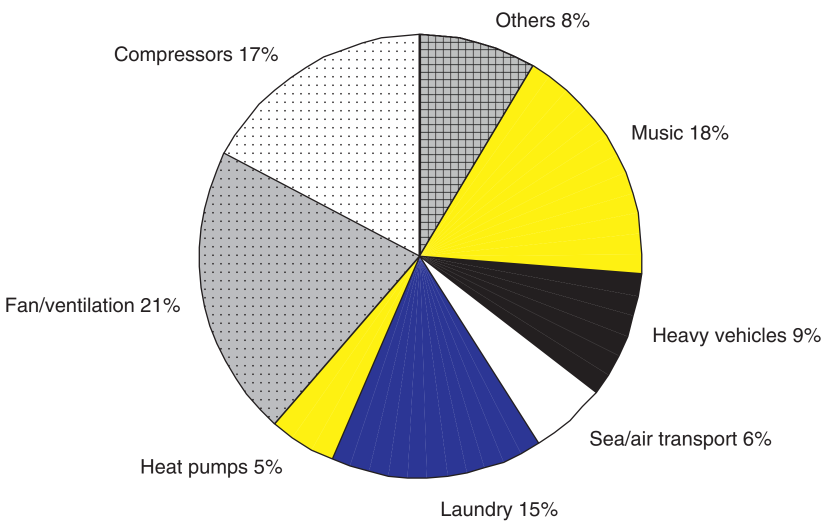

Figure 3 One indication of the relative proportion of sources in the general environment leading to complaints on low frequency noise. Reprinted from Bengtsson J and Persson Waye K (2003) Assessments of low frequency noise complaints among the local Environmental Health Authorities and a follow-up study 14 years later. *Journal of Low Frequency Noise, Vibration and Active Control* 22(1): 9–16, with permission.

structure-born sounds and in combination with vibrations, the occurrence of complaints may be distinctly higher. An indication of the relative proportion of sources leading to the greatest number of complaints on low frequency noise from one study is given in Figure 3.

Hearing and Perception of Low Frequency Noise

The frequency range of 20 Hz to 20 kHz is conventionally referred to as the human audible range. This is also the frequency range where the normal hearing threshold has been standardized. The normal hearing threshold is defined as the median level at which, under standardized conditions, otologically normal persons between 18 and 25 years give 50% correct responses in repeated tests. In contrast to what can be found at frequencies above 1000 Hz, the effect of age has been found to be of less relevance for hearing of low frequencies, and the age-related impairment has been estimated to approximately 10 dB for the median threshold for frequencies below 160 Hz. The hearing thresholds below 20 Hz have been investigated in quite a few studies, and although not yet

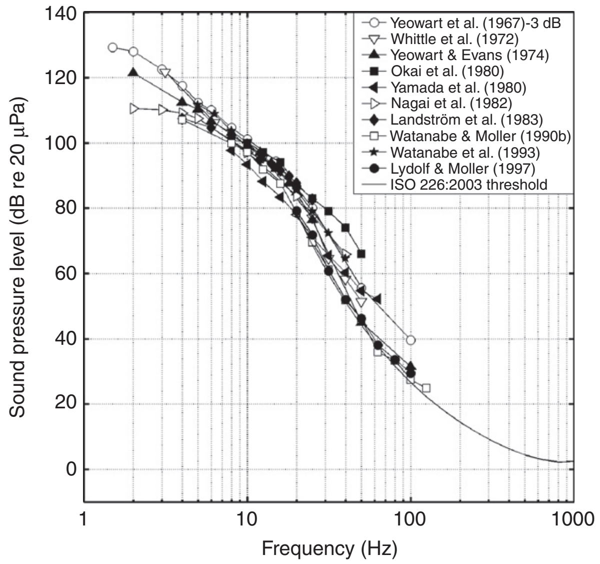

Figure 4 Results from recent investigations covering frequencies at and below 20 Hz. Whittle et al. weighted average of 30- and 43-year groups; Yeowart and Evans weighted average of ear and full-body exposures; Yamada et al. weighted average of men and women. The standardized hearing threshold above 20 Hz also included. Reprinted from Møller H and Pedersen CS (2004) Hearing at low and infrasonic frequencies. *Noise & Health* 6(23): 37–57, with permission.

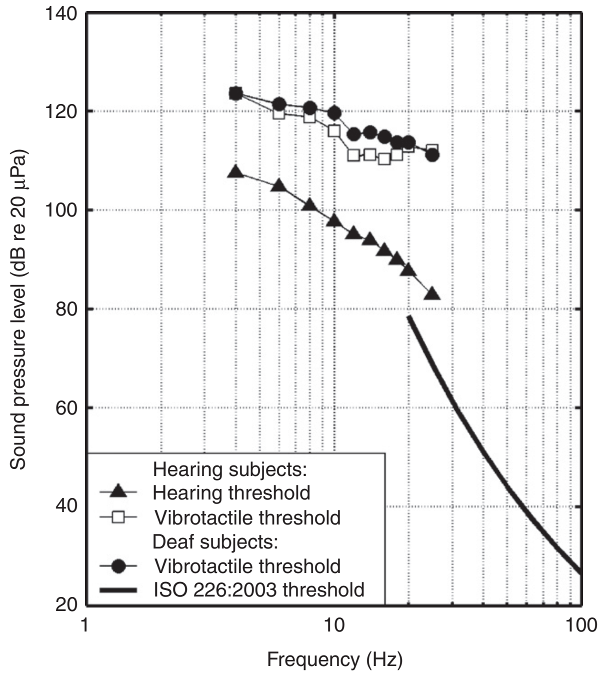

Figure 5 Hearing and vibrotactile thresholds as measured for hearing and deaf subjects. Reprinted from Møller H and Pedersen CS (2004) Hearing at low and infrasonic frequencies. *Noise & Health* 6(23): 37–57, with permission.

standardized, there is now a general acceptance for the hearing threshold, down to at least 2 Hz, being in the range shown in Figure 4. The perception changes from a tonal character above approximately 16 Hz to a sensation of pulses or pressure variations of the eardrum below this. As can be seen in Figure 4, the threshold is steep toward the lowest frequency range, meaning that to hear the infra-frequency range, the levels need to be high, at 2 Hz around 120 dB and at 20 Hz around 78 dB. The practical implication of this is that individuals are rarely exposed to audible sounds in the infra-frequency range in the general environment. Exposure to audible infrasounds may, although, occur in some occupational settings with combustion processes, large machines, and so forth. Figure 4 also displays that the levels needed to hear low frequencies at least above 25 Hz are less extreme and will more frequently be found both in the general environment and in the occupational environment. Many of the occasions where infrasound disturbance is reported can hence be referred to sounds in the low frequency range.

As for the perception of sounds in general, the hearing organ is also the most sensitive organ for infra- and low frequencies. In addition, at levels somewhat above the hearing thresholds, sensations also occur as vibrations in different parts of the body, most often reported in the chest, stomach, and buttock. By exposing persons with complete sensoneural and perceptive deafness, such vibrotactile thresholds have been found (Figure 5).

Equal Loudness

Loudness is the subjectively perceived intensity of a sound, and the equal-loudness-level contours are made up by subjects' perception of tones of different frequencies and intensities, judged to be as loud as a reference tone at 1 kHz (Figure 6).

The standardized contours cover the frequency range of 20 Hz to 10 kHz. The distance between two curves is equal to a twofold increase in perceived loudness, which for 1 kHz is equal to 10 dB. This is, however, not directly applicable to the low frequency range, where the contours are nearer together. The distance between two contours at 63 Hz, for example, is dependent on the level, approximately 5–7 dB. To be perceived as twice as loud, it is enough for the level to increase with 5–7 dB, or stated in another way, a 10-dB increase at 50–63 Hz may be perceived as up to four times as loud.

Although less researched, similar frequency dependency seems to apply also for annoyance. In addition, there are a number of studies showing that the frequency range of 25–63 Hz may be especially unfavorable and annoying, indicating that the equal-annoyance contours may not be as smooth as the equal-loudness contours.

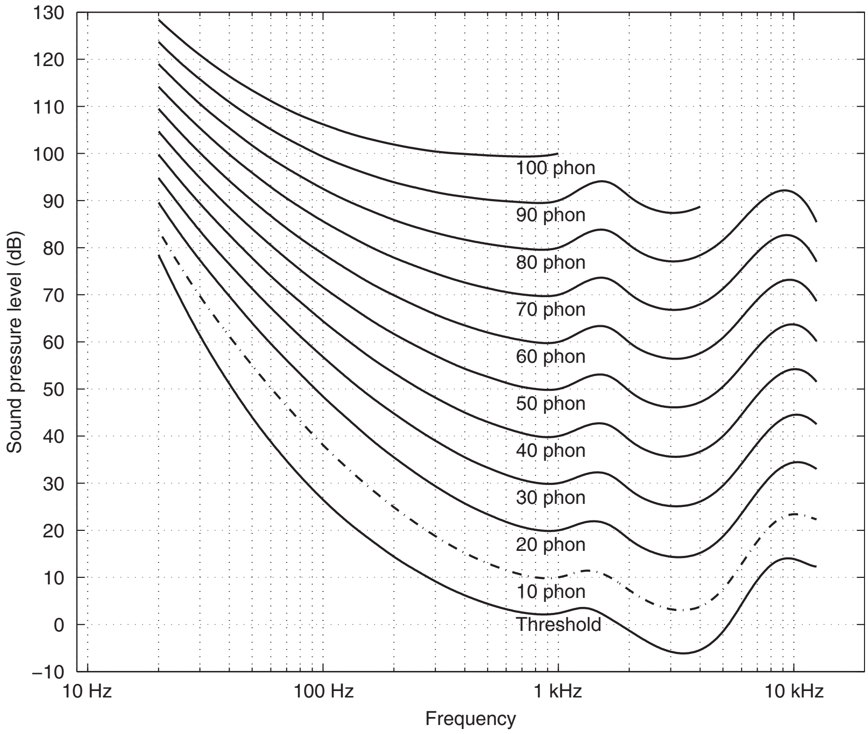

Figure 6 The normal equal-loudness-level contours. The terms and definitions are taken from the International Organization for Standardization (ISO 226:2003). Acoustics – normal equal-loudness-level contours – are reproduced with permission of the ISO. This standard can be obtained from any ISO member and from the Web site of ISO Central Secretariat at the following address: www.iso.org.

Adverse Effects on Health and Well-being

Subjective Symptoms

Compared with high frequency sounds, low frequency noise does not usually pose an immediate distraction. A common reaction to low frequency noise, and especially steady-state noise such as ventilation noise, is a feeling of relief when the noise ceases, even when the exposed persons have not been aware that the noise was present. It has been reported that about two-thirds of office employees experienced a subjective feeling of relief, whereas 16% were not aware of any difference, when the ventilation system was turned off at night. The current hypothesis is that the relief reflects a cessation of the mental load imposed when structures of the midbrain try to attenuate the steady-state signals from reaching higher centers of awareness. However, the mental energy needed to attenuate low frequency sounds does not seem to come without a cost, as both field and experimental studies imply that performance may be reduced over time. Although poorly researched, this finding supports the hypothesis that low frequency sounds are less well habituated to as compared to higher frequency sounds.

In a large number of case studies, the most commonly reported symptoms are headaches or a feeling of pressure in the head, unusual fatigue, concentration difficulties, irritation, vibrations in the body, and a feeling of pressure on the eardrum. Although these reports have been made on the basis of case studies and may thus have a number of sources of error, the agreement between them in terms of symptoms and sound descriptions is good. Some of these symptoms, such as lack of concentration, sleepiness, tiredness, irritation, pressure on the eardrums, and pressure in the head, have been found to be related to noise annoyance in experimental and field experimental studies. Only a limited number of epidemiological studies are available, all of cross-sectional design. From these, it can be seen that populations exposed to low frequency noise report disturbed rest and concentration to a higher degree, compared to controls. The prevalence of these symptoms also tends to increase with higher levels of low frequencies. In a study of 368 families exposed to infrasound, low frequency sound and vibrations from a motorway, the symptoms of headaches, irritation, sleep disturbance, a feeling of pressure in the head, pain in the arms and legs, and dizziness were significantly related to distance from the motorway. Comparisons were made with 98 families living at a greater distance from the motorway. As some of these symptoms can be associated with other stressors in the environment, the studies need to be large to fully correct for possible confounders, and further studies are needed.

Sleep Disturbance

Several case studies report that low frequency noise affects sleep quality, particularly with reference to the time taken to fall asleep and tiredness in the morning. A limited number of cross-sectional epidemiological studies have been carried out, which give some support to the findings in the case studies. In one of the few studies that have tried to relate the low frequency content in heavy vehicle noise to adverse effects, a significant correlation was found between the maximum levels of low frequencies in the noise, measured as LpCmax, and urine cortisol levels sampled in the first half of the night. The increase in cortisol was furthermore significantly related to impaired sleep, memory, and ability to concentrate. The results could indicate that long-term exposure to intermittent low frequency noise resulted in chronic increases of subjects' excretion of free cortisol in the first half of the night, and thus disturbance of the circadian rhythm. Similarly, the energy content of 20–160 Hz has been shown to be significantly related to sleep disturbance, concentration difficulties, irritability, anxiety, and tiredness. The limited number of experimental studies of low frequency noise has been ambiguous with regard to its effects on cortisol, whereas the negative influence of subjectively assessed sleep parameters is clearer.

Reduced Wakefulness/Greater Fatigue

An increased risk of drowsiness during exposure to infrasound has been reported in laboratory trials and field studies, with a positive correlation between exposure to infrasound at levels just above the perception threshold and reduced wakefulness. The reduced wakefulness is accompanied with reduced pulse, reduced systolic and diastolic blood pressure. All of these reaction patterns are normal physiological changes produced during falling asleep. Whether this effect also extends to the low frequency range is less well explored, although some data from the field and laboratory studies point in a similar direction. If continuous low frequency noise causes reduced wakefulness and attention, this could have serious consequences for professions where sustained attention is crucial, such as drivers, pilots, and control room workers.

Effects on Work Performance

The impact of low frequency noise on work performance can be understood to occur in different ways. Symptoms that have been reported in connection with annoyance due to low frequency noise and that could reduce work performance are fatigue, concentration problems, headache, and irritation. Possible mechanisms are suggested by studies where monotonous low frequency noise has been shown to have a sleep-provoking effect. If this is the critical mechanism, one would expect tasks that are known to be sensitive to a lowered wakefulness level also to be sensitive to low frequency noise, that is, primarily repetitive machine-paced tasks with high demands on sustained attention. Noise effects on performance can also be interpreted as the result of an information processing overload. As there are some indications that low frequency noise may be more difficult to habituate to, exposure to low frequency noise during mentally demanding work may lead to a higher competition of available resources and interfere with cognitive processing abilities. The effort to cope may thus be more strenuous for low frequency noise and could lead to a low-level stress reaction.

Although some studies have failed to identify significant effects, there is convincing support that low frequency noise may negatively affect performance at moderate levels occurring in office and control room environments. The effects have most clearly been shown for work situations with high demands and for tasks with high cognitive loading, where the effects appear over time. Figure 7 displays the results from a high-demand task carried out during exposure to two noises at equal A-weighted SPLs (40 dB) but with different spectral characteristics (50 versus 69 dB LpC). No differences in response times were found between the two exposure noises the first time the task was performed, however the second time, the response time was shorter when working in the flat-frequency ventilation noise. The same improvement was not found when working in a low frequency ventilation noise, indicating that low frequency noise impaired learning.

There are also indications that more routine-type tasks aimed at evaluating attention and vigilance are affected if studied over a longer time. For example, reduced learning was found in a signal detection test using recorded noise from a ferry boat, 70 dB LpA (A-weighted sound pressure level), and linear levels up to 90 dB in comparison to a flat-frequency sound at the same A-weighted SPL. Similarly, subjects in a low frequency ventilation noise (45 dB LpA, 72 dB LpC) needed a somewhat longer response time as compared to a flat-frequency ventilation noise (45 dB LpA, 53 dB LpC) to make decisions on an attention-demanding task, and despite this, they gave a greater number of erroneous answers.

Hearing Loss

Little information is available on permanent hearing impairment due to low frequency noise, and the risk evaluation is complicated by the fact that most occupational settings with low frequency sound also comprise sounds of higher frequencies. Most studies evaluating the risk for temporary threshold shift (TTS) of infrasound were conducted in the 1960s or 1970s and include a small

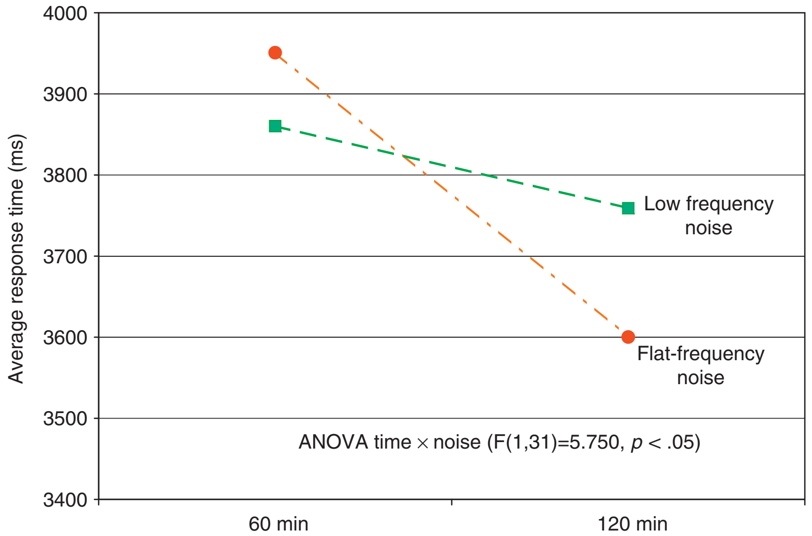

Figure 7 Average response time over time during work with a cognitive demanding task in low frequency noise (squared marks) and flat-frequency noise (round marks). Both noises had the same A-weighed SPL. Adapted from Persson Waye K, Bengtsson J, Kjellberg A, and Benton S (2001) Low frequency noise "pollution" interferes with performance. *Noise & Health* 4(13): 33–49, with permission.

number of test subjects. Those studies show that high levels of infrasound of more than 125 dB may induce TTS and that the recovery period tended to be longer for sounds in the upper part of the infrasound range. TTS induced by low frequency sound was investigated in one study comprising 35 men. Octave band noise centered at 63, 125, and 250 Hz at a level of 84 dB LpA for 24 h and 90 dB LpA for 8 h induced 10–15 dB TTS and lasted up to 48 h after the exposure.

The Influence of Non-hearing-mediated Experiences of Low Frequency Noise

In addition to the direct experience of low frequency noise via the auditory system, low frequency noise at sufficiently high SPLs induce vibrations mainly in the chest and stomach. A marked resonance around 60 Hz of the chest was found during exposure to high levels of low frequency sounds in experimental studies and in the field among flight technicians.

During the past 20 years, one research group has reported information of a multi symptom disease called vibro-acoustic-disease (VAD). VAD has essentially been defined as a noise-induced disease caused by long-term exposure (ten years or longer) to high sound pressure levels (>90dB SPL) at frequencies below 500Hz. It is described to involve abnormal profileration of extra cellular matrices (collagen and elastin) particularly in the cardio-respiratory system with the absence of inflammatory processes. Some of the findings related to the respiratory tract, the cochlea and genotoxic effects have been reproduced in animal models. The epidemiological studies of VAD were described primarily among flight technicians exposed for long periods, more than 10 years, to high levels of broadband aircraft noise and more scientific studies are needed before it is possible to draw conclusions of the risk for other groups in the society.

Annoyance

Noise-induced annoyance is the most common and most researched adverse effect of noise on people. This is also the case for low frequency noise. Annoyance has been defined as 'a feeling of displeasure evoked by a noise' and 'any feeling of resentment, displeasure, discomfort, and irritation occurring when a noise intrudes into someone's thoughts and moods or interferes with activity.' Annoyance is measured using questionnaires or interviews and the rating is usually done on a verbal or numeric scale with endpoints 'not at all annoying' to 'very' or 'extremely annoying.'

The majority of case studies on low frequency noise carried out in general environments (indoor and outdoor residential areas) and work environments report that annoyance occurs even though the A-weighted SPLs are within permitted limits for ordinary noise in the different countries in which the studies were carried out. Furthermore, annoyance has been found to be significantly higher in populations exposed to steady-state low frequency noise as compared to steady-state flat-frequency noise, and the prevalence of annoyance has been found to increase with higher low frequency SPLs. Also, numerous experimental studies have found that the A-weighted SPLs underestimate annoyance caused by low frequency noise (Table 1). The experimental studies have adopted different strategies from adjustments or tuning of the

Table 1 Studies where the applicability of the A-weighted level has been assessed for low frequency noise

Type of study	*Method*	*Exposure*	*Main findings*
Experimental	20 subjects adjusted a sound to equal annoyance of the other. Exposure time: 10 s.	Two broadband sounds with high versus low proportion LF, 49–86 dBA.	dBA underestimated annoyance of the LF noises with 5 dB at 50 dBA and 8 dB at 86 dBA.
Experimental	12 subjects matched a sound to equal annoyance of the other.	A broad band noise and three LF noises with different steepness of the slope towards the higher frequency range.	dBA underestimated annoyance of the LF noises and dBC overestimated annoyance.
Experimental	3 times 20 subjects in between design, rated annoyance on a four-graded verbal and 100-mm graphical scale after 30-min exposures.	Two ventilation noises with the center frequencies of 80 and 250 Hz, at 40, 50, 55, 60, 65, and 70 dBA.	The 80-Hz LF noise is significantly more annoying than the 250-Hz ventilation sound at 60, 65, and 70 dBA.
Experimental	In total, 98 subjects (20 in each group) in between design, rated annoyance after 30-min exposures.	Four ventilation noises with the center frequencies of 80, 250, 500, and 1000 Hz, at 40, 50, 55, 65, and 70 dBA.	The underestimation of the dBA weighting was frequency and level dependent. For the 80-Hz LF noise, the underestimation was 3.5 dB at 65 dB SPL and 6.5 dB at 75 dB SPL.
Experimental	2 times 24 subjects in between design, tuned in the highest acceptable level for performance of routine and complex tasks. Exposure time: 15 min.	Broadband noises centered at 100 and 1000 Hz.	Acceptable level was 6 dBA lower for the LF noise.
Quasi-field study	145 male control room workers rated annoyance on a 100-mm graphical scale, after 20-s exposures.	Four recorded samples of LF noise and four samples of an FF noise, 68–93 dBA, and 62–84 dBA, respectively; exposed via headphones in a quiet room at work.	The LF sounds were rated as significantly more annoying. The difference between equal annoyance as assessed by linear dose–response relationships amounted to 9–10 dB.
Experimental	32 subjects performed different cognitively demanding tasks at high-workload conditions during 120-min exposures. Rating of annoyance after the work session on a 100-mm graphical scale.	LF ventilation noise and FF ventilation noise, both at 40 dBA.	The LF sound was rated as significantly more annoying than the FF sound. Subjects classified as highly sensitive to LF were more annoyed than subjects less sensitive to LF sounds.
Experimental	38 subjects performed different cognitively demanding tasks at low-workload conditions during 240-min exposures. Rating of annoyance after the work session on a 100-mm graphical scale.	LF ventilation noise versus FF ventilation noise, both at 45 dBA.	No significant difference of annoyance between sounds was found.
Experimental	In total, 191 subjects performed tasks of different cognitive demands during 60-min sessions. Rating of annoyance on a 100-mm graphical scale.	LF noise at 51 dBA and FF noise at 51 dBA, background noise at 41dBA.	No significant difference of annoyance between the exposure sounds, subjects classified as highly sensitive to noise were more annoyed in the LF noise as compared to low sensitive.

LF, low frequency; FF, flat frequency.

level of the low frequency sound to become equally annoying as a 'non' low frequency sound or flat-frequency sound, to long-term exposures in experimental conditions. There is also one quasi-experimental study where control room workers were exposed to low frequency sounds and broadband flat-frequency sounds through headphones in a quiet room. In all studies, except two, significant differences between exposures were found showing that the low frequency sound was judged as more annoying or less acceptable at equal A-weighted levels. It can, therefore, rather safely be concluded that the A-weighting underestimates the annoyance potential of low frequency sound, and the degree of underestimation seems to be level and frequency dependent and is in the range of 4–10 dB.

Several attempts have been made to replace the A-weighting with another noise descriptor. A general finding between studies where correlation coefficients are obtained between annoyance and different standard measures, such as A- and C-weighted decibels, C–A-weighted decibels, A-weighted within 10–160 Hz (LpA, LF), or A-weighted within 10–80 Hz (LpA10-80), is that a rather high correlation is obtained for most measures, and that no significant differences between weightings are detected. This can be explained by the fact that most measures are interrelated; hence, correlations may not be the best way of evaluating a potential difference. The use of equal-loudness-level contours has also been suggested. Interestingly, annoyance to different low frequency noise sources corresponded best to the old version of the equal-loudness-level curves and when the sounds were being filtered to correspond to an indoor environment with the window slightly opened.

The response, although, is likely, in addition to loudness, to be related to other factors related to the intrusiveness of the sound and for higher levels of low frequency noise also vibrations and oppressive feelings In addition to loudness, the response is likely to be influenced by other factors related to the intrusiveness of the sound and for higher levels of low frequency noise also vibrations and oppressive feelings. (See section on 'Specific acoustic characteristics' below).

Dose–Response Relationships

As many transportation noises comprise low frequencies, a great deal of previous studies could have also given input to effects due to low frequency noise. However, these studies seldom include other acoustical information, except the A-weighted SPL, and indoor measurements. Owing to this lack of information, the best guess has to be deduced from a small number of studies carried out in residential areas. A recently derived dose–response curve based on a total of 1875 respondents and calculated A-weighted day–evening–night average sound levels (Lden) from stationary sources from industries classified as 'seasonal,' 'shunting yard,' and 'other type' also lend some guidance. Of the industries, only 'shunting yards' would, at least during winter when diesel engines operate, emit a low frequency noise; however, shunting yards also produce impulse noise that considerably increase the risk for noise annoyance. The curves derived are plotted in Figure 8.

A study of stationary sources comprising different amounts of low frequencies could be compared to this curve. Sounds from compressor and ventilation units, as part of a total urban soundscape, were studied among 473 residents living in apartments surrounding courtyards exposed to traffic noise on one side of their apartments and to sounds from compressor/ventilation units on the other side, chosen to comprise a gradient in low frequency exposure. Measurements were done outdoors and indoors. Figure 8 displays the proportion of subjects annoyed by sounds from compressor/ventilation units in the eight areas related to the curves for shunting noise and other industrial noise.

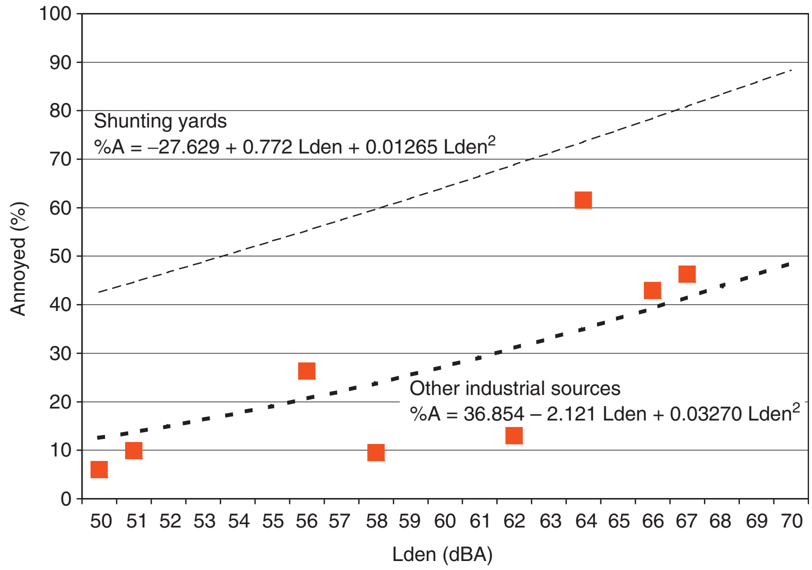

Figure 8 Curves showing the expected percentage of annoyed as a function of Lden, for shunting yards and industry. Reprinted from Miedema HE and Vos H (2004) Noise annoyance from stationary sources: Relationships with exposure metric day-evening-night level (DENL) and their confidence intervals. *The Journal of the Acoustical Society of America* 116(1): 334–343, with permission from American Institute of Physics. Also shown the prevalence of noise annoyance due to low frequency noise annoyance from compressor and ventilation units obtained in a separate study (filled squares). From Persson Waye K and Agge A (2005) The importance of the immediate soundscape for annoyance in the urban environment. *The 2005 Congress and Exposition of Noise Control Engineering Inter-Noise*, 10 pp. Rio de Janeiro, Brazil.

The data in Figure 8 clearly need to be complemented by further studies where a distinction is made between different acoustical characteristics of the stationary sources. Owing to selective attention of structures as mentioned in the section 'Introduction' and room resonances mentioned in the following text, valid assessments of low frequency noise need to rely on measurements indoors. If data obtained from the study of compressor and ventilation units, displayed as squares in Figure 8, is analyzed based on indoor measurements, a considerably better fit was obtained. For example, when relating the annoyance to measured A- or C-weighted sound levels indoors, with the window slightly opened, the determination coefficients (r^2) obtained were as high as 0.95 and 0.96, respectively.

For the occupational environment, there are generally less data to derive dose–response relationships for sounds in general, and this is also the case for low frequency noise. Deriving dose–response relationships in the occupational environment is also complicated by the fact that tasks and demands play a role for the risk of being annoyed. Hence, dose–response curves probably need to be derived for various categories of demands. In office environments, where most data are gathered, it can be estimated that more widespread annoyance would occur if the A-weighted levels of the low frequency exposure would be above approximately 38–40 dB.

Specific Acoustic Characteristics of the Importance for the Response

Ample data show that several acoustic characteristics apart from level seem to be of importance for the intrusiveness of low frequency noise. The perceptual characteristics in low frequencies, such as the pulsating or throbbing characteristics, and the dominance of low frequencies in relation to the higher frequencies, sometimes referred to as unbalanced spectra, are factors that need to be taken into account for an improved assessment of low frequency noise. These, in combination with the often-steady nonintermittent exposure (sound always there), are believed to have great influence on noise annoyance.

Frequency Balance

The importance of the spectrum balance, that is, the content of low frequencies in relation to the content of higher frequencies, has been in focus since the 1970s. Based on empirical findings, it was concluded that a spectrum with a falloff of −5.7 dB per octave above 31.5 Hz was acceptable, whereas a spectrum with a falloff of −7.9 dB per octave above 63 Hz was unacceptable. Subsequent measurements of air-conditioning noises in offices found that an acceptable spectrum had a slope of −5 dB per octave. In addition, later studies reported that a frequency spectrum with a slope of approximately −4 dB per octave was considered neutral, whereas a slope of −6 dB per octave was considered as 'strong rumble.' Following this line of thinking, experiments have been carried out to test this aspect more in detail. In experiments where the A-weighted SPL was kept constant, the general findings in the field studies were confirmed. It was furthermore found that the slope that was considered most acceptable/pleasant was dependent on whether the sound comprised level fluctuations or not. The slope of a pleasant sound with modulations was approximately −4.4 dB per octave, whereas the slope of the pleasant sound with no modulations was approximately −6.2 dB per octave. In addition, equal unpleasantness curves obtained experimentally for tones were found to have a slope of −6 dB per octave. Figure 9 summarizes some of the most important findings.

As can be seen in Figure 9, there are deviations as to where the slope begins to fall off; for example, the unacceptable slope of Bryan starts to fall off above 63 Hz. The most important problem with the slope concept is, however, that it is not clear how to practically cope with the slope model, as the values of the slope will vary depending on where it is fitted to the frequency spectra and probably also with SPLs. Keeping these problems in mind, it is, however, interesting to note the comparatively large agreement with the different studies as to what slope is unacceptable or strong rumble versus what slope is considered to be acceptable, neutral, or pleasant (if the sounds comprise modulations). A 'good' slope seems to be in the range of 4 dB per octave, whereas a 'bad' and potentially annoying sound seem to have a slope of around 6–7 dB per octave or more.

Level Fluctuation

The pulsating character of low frequency noise can be a result of level fluctuations in amplitude of an individual frequency, level fluctuations caused by two close maxima or of a sequence that varies over time in a smaller part of the frequency spectrum. Level fluctuating low frequency noise have been indicated to enhance adverse effects on performance and reductions in alertness although few studies have made direct evaluations of these effects and the presence of the acoustic characteristic. There is, however, an accumulated body of field and experimental data showing that rapidly fluctuating low frequency sounds have a lower acceptability threshold and will also increase unpleasantness and annoyance. From experimental studies where subjects have been asked to adjust sounds of different degree of modulations to be equally annoying as a neutral spectra or studies where subjects have been asked to adjust a low frequency sound to

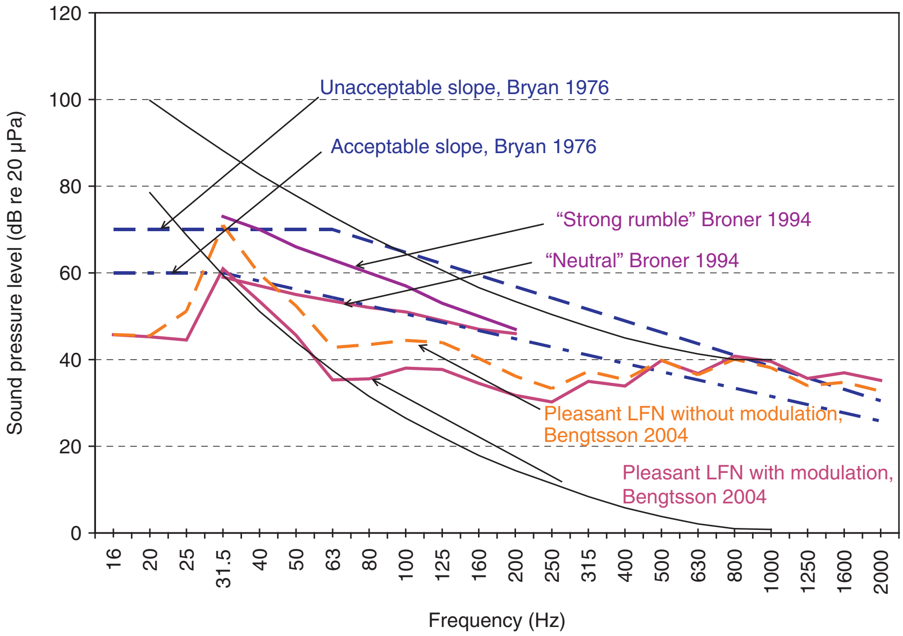

Figure 9 'Unacceptable' and 'acceptable' frequency slopes of low frequency sounds. Included are also the 40-phon curve (ISO 226:2003) and the normal hearing threshold (ISO 389-7:2005). Adapted from Persson Waye K (2005) Adverse effects of moderate levels of low frequency noise in the occupational environment. *ASHRAE Transactions* 111: 672–683, with permission from ASHRAE.

become as pleasant as possible within a fixed A-weighted SPL it is seen that the presence of modulations contributes to approximately a 10- to 12-dB difference of annoyance/unpleasantness (Figure 9). The results are somewhat dependent on the modulation frequency, but most studies show the frequency range of 0.5–4 Hz as being most unpleasant/annoying. Interestingly, this is largely in accordance with what have been found to be the frequency modulation where the hearing is most perceptive also for tones of higher frequencies. This characteristic in low frequency sound is thus highly significant. The psychoacoustic measure of fluctuation strength has not proved to be successful, and a method for better quantification is needed.

Vibration

In many workplaces and living environments, low frequency noise may occur in combination with vibrations. Although annoyance due to airborne noise has been found to be greater in combination with vibrations, less information is available about the combined effects of low frequency noise and vibration. Furthermore, it can be expected subjects confuse the exposures, having difficulty differentiating between the sensation of vibration and noise. Present data indicate, although, that a combined exposure would increase annoyance. Apart from sound emissions from vibrating building elements, secondary phenomena may occur in the form of rattling doors, clattering china, and glass panes. These phenomena are reported to significantly increase the annoyance and have typically been reported in more lightweight built houses, in connection to aircraft takeoff and heavy artillery, and at a distance from highway bridges and high-speed trains.

Individual Factors of Importance for the Response

Subjective Sensitivity

For noise in general, the individual factor that is most clearly related to noise annoyance is hearing impairment, where people usually are more disturbed by noise. It has also been found that people who characterize themselves as noise sensitive are more annoyed by noise, show stronger physiological response to noise, and perform a task less well in noise. Subjective noise sensitivity is believed to be a stable personality characteristic; however, it has not been established whether noise sensitivity reflects a sensitivity specifically to noise or a more general sensitivity to environmental factors.

General experience gained in case studies show that people who become annoyed by low frequency noise develop a specific sensitivity to low frequency noise sources, although they rarely consider themselves to be sensitive to noise in general. In agreement with this, when experimentally investigated, sensitivity to noise and sensitivity to low frequency noise were not found to correlate.

Cases with an Enhanced Susceptibility to Low Frequency Noise

There are ample reports of people being under great distress of a low frequency noise often not heard by others. These people are often referred to as low frequency noise sufferers, and the noise is sometimes named 'the Hum.' The causes of its presence and effects are not clarified; however, it has been found that low frequency noise sufferers set the threshold level for acceptability just above their threshold of hearing. Hence, the prerequisite for annoyance seems to be bare audibility for these cases. The normal threshold as outlined in the previous section represents the median value and standard deviations between young normally hearing individuals amount to approximately 5 dB, regardless of frequency. From this, it can be estimated that approximately 2.5% of the population has a hearing that is below 10 dB of the normal hearing threshold. It has been suggested that this would be a reason for excessive annoyance at very low level low frequency noise; however, there is little or no support for this hypothesis. It has also been found that the threshold of hearing, if measured in narrow frequency steps, may exhibit dips where the hearing may be considerably more sensitive. The importance of such sensitivity for individual annoyance to low frequency sounds has not been confirmed.

From other areas of research, it has been found that the brain possesses plasticity, and that extensive stimulation can enhance different regions of the cortical area. It is furthermore thought that the amygdala complex and the amygdala nucleus in particular contributes to the emotional response connected with, for example, fear and anxiety and that it may, in connection with other brain regions, influence processes by which sensory stimuli gain significance and get assessed. Although not verified, it could be that an initial adverse response to a low frequency noise, especially if the source is unknown, could make a person attentive to the sound. If no support is given, that is, by the lack of authoritative actions and due to the subject not successfully coping with the situation, hearing the sound could elicit increased emotional reactions, including psychophysiological responses that, if repeated, could have adverse health consequences.

The possibility that the cause is not a physical noise has been proposed. A most recent study found in about a third of the investigated cases that a low-level external noise was responsible for the complaints, although it failed to find an external noise being responsible for the effects in about another third of the cases. For those, an internal sound, referred to as low frequency tinnitus, was the most probable cause. It should be noted that in spite of rigorous measurements in the complainants' homes and blind tests in the laboratory, there was one-third of the cases for which the reasons for the complaints could not be established. Furthermore, none of the complainants had an extraordinary hearing threshold, and infrasound was not found to be the cause of the annoyance. To properly evaluate these cases and relieve people from long-term distress, the cases need to be handled professionally. To facilitate this, complaint procedures have been developed in some countries, for example, the UK, the Netherlands, and Japan. Also, correct measurement methods are highly important to establish if a perceivable low frequency sound is present (see the section 'Assessments').

Assessments

To overcome the inherent problem with the A-weighting, low frequency specific exposure criteria are in use or are proposed in some countries for the living environment. Generally, all of them are based on the frequency analysis in 1/3 octave bands, the included frequency range varying between 8 and 250 Hz. In the majority of cases, measured SPLs are compared to criterion curves. Exceptions are the Danish and German methods. The Danish guideline is achieved by applying the nominal A-weighting to the 1/3 octave bands and summing the weighted 1/3 octave bands within the frequency range of 10–160 Hz to form the LpA LF. A further penalty of 5 dB is added for impulsive noises. The German method states, for nontonal noises, that the A-weighted SPL in the 10–80 Hz frequency range (LpA, 10–80 Hz) is calculated based on 1/3 octave bands exceeding the normal hearing threshold. For tonal noise, however, the level of the 1/3 octave band with the tone is compared to the hearing threshold, and different penalties are added depending on the frequency of the tone and the time of day. The Polish method also takes the background noise into account when assessing annoyance. In Figure 10, the curves of the above-mentioned assessments are displayed.

Only a few countries have adopted guidelines for assessments of occupational low frequency noise. In the United States, there are recommendations for noise from heating ventilation and air-conditions based on limit values in third octave or octave bands (curves or noise ratings). These noise ratings have their origin in the 1950s and have been modified a number of times. In Europe only, Sweden and Denmark have guidelines, covering about the same categories of workplaces, that is, workplaces with a high demand on cognition, concentration, and speech, such as offices and schools. Infrasounds are usually assessed by adopting the G-weighted SPL, the exact criterion values differ somewhat between countries.

Aspects Related to Measurements of Low Frequency Noise

Owing to the frequency-selective attenuation of low frequencies by building constructions mentioned previously,

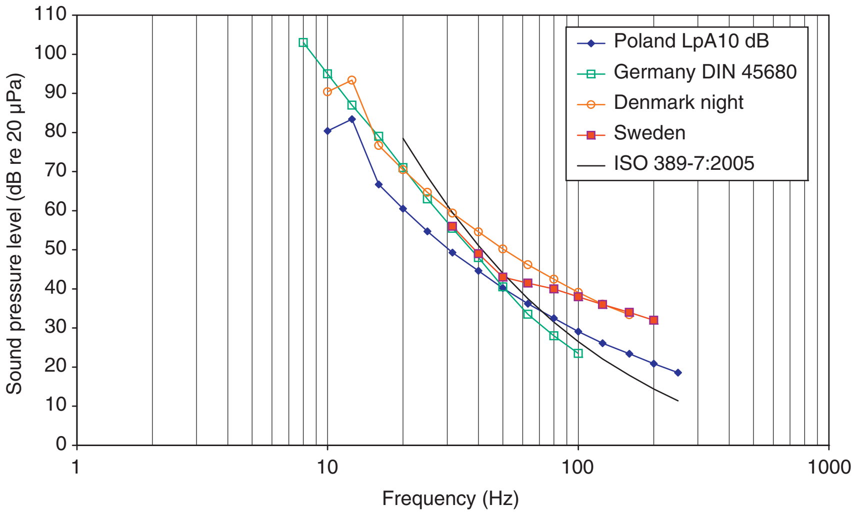

Figure 10 Curves used for assessment of low frequency noise in the general environment.

it is not possible to get a correct measure of people's exposure based on outdoor measurements. Moreover, indoors the reflections of low frequencies by the walls, ceiling, and floor will result in a pattern of high and low SPLs, so-called standing waves. The standing waves may lead to variations in level amounting to as much as 20–30 dB for pure tones and somewhat less for noise bands. Understandingly, this may lead to great uncertainties in the measurement results. An important factor to be resolved is how indoor measurements should be best carried out not only to be reliable but also to reflect the subjective annoyance. People seem to react to the highest levels, making it important to incorporate these levels in the measurements. The methods that are in use today can give large differences when measuring the same source, and this aspect needs to be properly addressed. As stated previously also, various acoustic parameters are of importance for effects. It is advised to include detailed frequency spectral measurements, at least in third octave bands, temporal characteristics, and, if present, also vibrations.

Conclusions and Suggestions for Further Research

Low frequency noise is widely spread in today's society, and adverse effects may occur at very low SPLs. There is an increasing acceptance that low frequency noise needs to be specifically attended to, but only a few countries have adopted specific guidelines for low frequency noise.

There are also accumulative data of adverse effects related to the exposure of low frequency noise; however, there are also many gaps to be filled to draw conclusive results. The following point to some areas where more research is needed.

There is a general need for epidemiological studies with valid and reliable assessments of low frequency noise exposure and human perception and response. To obtain valid assessments, although, more data on the connection between human response and sound exposure are needed. Of specific importance are intervention studies where the low frequency noise is eliminated or attenuated. These types of studies would, apart from data on dose–response relationships, also give a valuable contribution to the identification of other health symptoms apart from annoyance. The individual factors and the processes of habituation or sensitization are also highly interesting.

Sleep disturbance deserves specific attention, and both experimental and epidemiological studies are needed.

The consequences on health and performance of occupational exposure generally to low frequency noise and specifically to high SPLs, with or without vibrations, are other areas where further research is urgently needed.

See also: Mental Health Effects of Noise, Noise and Health: Annoyance and Interference.

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