Sources and effects of low-frequency noise

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The sources of human exposure to low-frequency noise and its effects are reviewed. Low-frequency noise is common as background noise in urban environments, and as an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and ventilation or air-conditioning units. The effects of low-frequency noise are of particular concern because of its pervasiveness due to numerous sources, efficient propagation, and reduced efficacy of many structures (dwellings, walls, and hearing protection) in attenuating low-frequency noise compared with other noise. Intense low-frequency noise appears to produce clear symptoms including respiratory impairment and aural pain. Although the effects of lower intensities of low-frequency noise are difficult to establish for methodological reasons, evidence suggests that a number of adverse effects of noise in general arise from exposure to low-frequency noise: Loudness judgments and annoyance reactions are sometimes reported to be greater for low-frequency noise than other noises for equal sound-pressure level; annoyance is exacerbated by rattle or vibration induced by low-frequency noise; speech intelligibility may be reduced more by low-frequency noise than other noises except those in the frequency range of speech itself, because of the upward spread of masking. On the other hand, it is also possible that low-frequency noise provides some protection against the effects of simultaneous higher frequency noise on hearing. Research needs and policy decisions, based on what is currently known, are considered. © *1996 Acoustical Society of America.*

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SOURCES AND EFFECTS OF LOW-FREQUENCY NOISE

The industrialization and mobilization of human endeavor have led to increased noise production across the full range of noise frequencies, leading to a global problem of reduced human well-being due to noise (see, e.g., Hede and Bullen, 1982; Kihlman, 1993; Schultz, 1978; WHO, 1980). The effects of noise on humans have been extensively reviewed, but apart from hearing loss (King *et al.*, 1992; Kryter, 1985, 1994; Ward, 1993) and annoyance (Fidell *et al.*, 1991; Job, 1988) are not uniformly agreed upon (Andersson and Lindvall, 1988; Berglund *et al.*, 1986; Berglund *et al.*, 1990). Low-frequency noise is a common component of occupational and residential noise which has received less attention. However, low-frequency noise has features not shared with noises of higher pitch. Low-frequency noise (infrasound included) is the superpower of the frequency range: It is attenuated less by walls and other structures; it can rattle walls and objects; it masks higher frequencies more than it is masked by them; it crosses great distances with little energy loss due to atmospheric and ground attenuation; ear protection devices are much less effective against it; it is able to produce resonance in the human body; and it causes great subjective reactions (in the laboratory and in the community studies) and to some extent physiological reactions in humans than mid- and high frequencies. These features dictate that the effects of low-frequency noise deserve independent attention. The present review considers low-frequency noise exposures and their physical, physiological, and psychological effects on humans.

I. DEFINITION OF LOW-FREQUENCY NOISE

The range of human hearing is generally considered to be 20–20 000 Hz for young individuals, the upper limit declining with increasing age. Frequencies above 20 kHz (ultrasound) are generally considered to be inaudible by convention (see Kryter, 1985, p. 456), even though frequencies up to 30 kHz have been ''heard'' through bone conduction (as cited by Yeowart, 1976). The focus of the present review is on the lower end of the frequency spectrum. In selecting the frequency range, we decided to treat low-frequency noise as including what is normally taken to be infrasound (see Fig. 1).

There are three reasons for this decision. First, sound below 20 Hz is generally termed infrasound and not included in low-frequency noise on the grounds that it is inaudible (see, e.g., Backteman *et al.*, 1983a). However, sound below 20 Hz can be perceived by humans, reflecting interindividual differences in hearing threshold. This is shown in Fig. 2,

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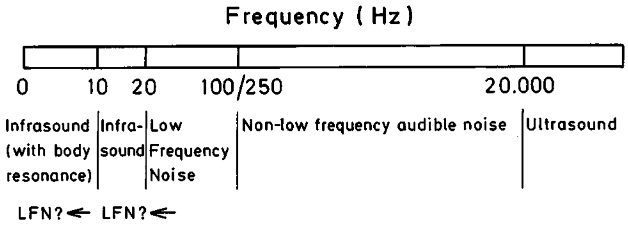

FIG. 1. The frequency spectrum of sound and its nomenclature.

which presents a compilation of hearing thresholds as a function of signal frequency.

The setting of the arbitrary lower limit of human hearing determines the lower limit of low-frequency noise and the upper bound of infrasound. Such a setting is not a matter of absolutes. The threshold of hearing for tones and frequency bands depends on the loudness as well as the frequency and duration. In this sense, logically, human hearing capacity extends well below the 20-Hz range if one considers a signal that is sufficiently loud (see Fig. 2). Thus the threshold of absolute hearing extends well into the nominal infrasound range. It has been suggested that at very low frequencies human detection does not occur through hearing in the normal sense. Rather, detection results from nonlinearities of conduction in the middle and inner ear which generate harmonic distortion in the higher, more easily audible frequency range (von Gierke and Nixon, 1976). This account does not dictate that the noise is not heard, but rather that the method of hearing is indirect, as indeed is the mechanical method of all hearing (i.e., the relevant nerves are fired by changes in other biological structures in the ear, not directly by noise itself).

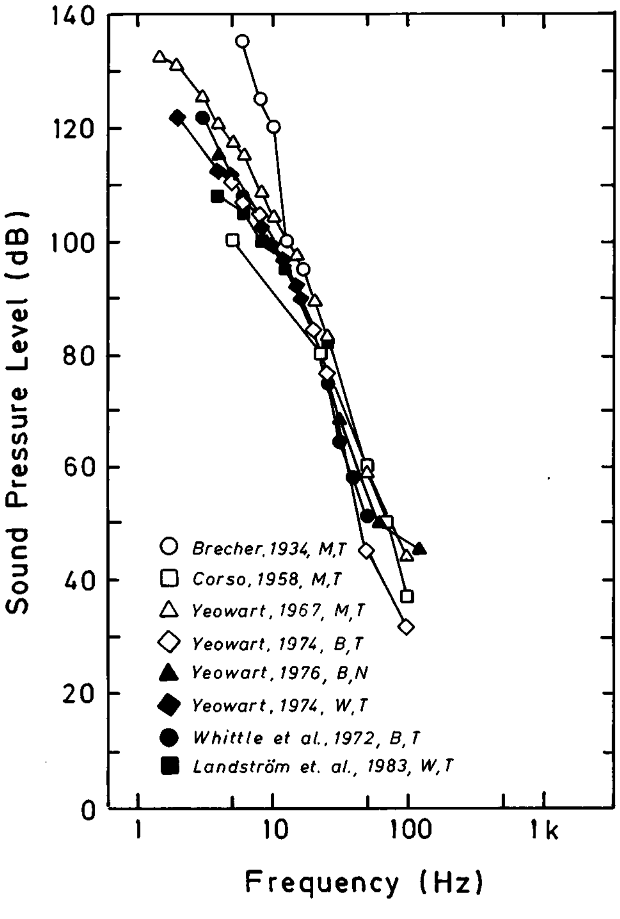

FIG. 2. Hearing thresholds as a function of signal frequency in various studies (M=monaural; B=binaural; W=whole body; T=tone; N=noise band).

Second, regardless of the process by which a sound wave is detected, it is critical to consider waves which are detected through skeletal bones, the ear, harmonics, tactile senses, or resonance in body organs. Detection raises the possibility of subjective reactions such as annoyance, and annoyance may contribute in complex ways to other biological and psychological effects of the signal (Job, 1993; Stansfeld, 1992).

Third, determination of health and other effects of low-frequency noise must consider field data. Real occurrences of low-frequency noise will often include considerable energy below 20 Hz as well as energy in what is usually considered the low-frequency noise range. Thus the arbitrary setting of a cutoff at 20 Hz is not conducive to analysis of such data.

The determination of precisely what constitutes *low-frequency* sound is also not perfectly clear in terms of its upper limit. Sound up to 250 Hz are sometimes referred to as low-frequency sound although others have set the upper limit of the range to 100 Hz (e.g., Backteman *et al.*, 1983a). Inevitably, the same problems of setting an arbitrary limit on a continuum apply to the upper limit of low-frequency noise as to the lower limit. However, given that there is no suggestion that the upper limit is in fact marked by a qualitative shift such as audibility to inaudibility, this cut point is not as critical. In the present review noise below 250 Hz is considered to constitute low-frequency noise.

As implied by the word ''noise,'' low-frequency noise is defined as an unwanted sound containing major components within a specified frequency range. Thus it depends, among other things, upon the complex temporal pattern and intensity of the sound, which determine whether the sound will be labeled as noise or as ''meaningful'' sound such as music or speech. Such classification also depends on cultural factors (Kuwano *et al.*, 1991), the individual (what one person hears as music another may consider unwanted sound), and on time and circumstances (a Mozart symphony may be music at dinner time but noise in the middle of the night when one is awakened from sleep: see Job, 1993).

II. SOURCES AND TRANSMISSION OF PROPERTIES

Sources for low-frequency noise are either of a natural origin, such as air turbulence (wind), thunder, ocean waves, volcanic eruptions, and earthquakes (von Gierke and Parker, 1976; Backteman *et al.*, 1983a), or of human origin such as heating, ventilation, air-conditioning systems, machinery, cars, trucks, airplanes, and loudspeaker systems (Blazier, 1981; Backteman *et al.*, 1983a, 1983b). In terms of effects on humans, artificial noises are more important because people react more to them (von Gierke and Parker, 1976), probably because of their attitude to the source (Job, 1988). The extent of exposure to low-frequency noise from trans-

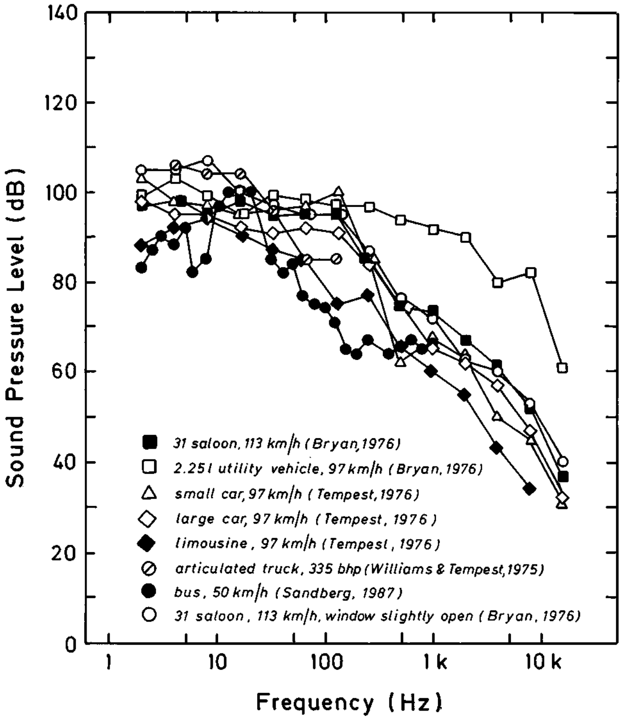

FIG. 3. Passenger noise exposure in road transportation vehicles as a function of frequency.

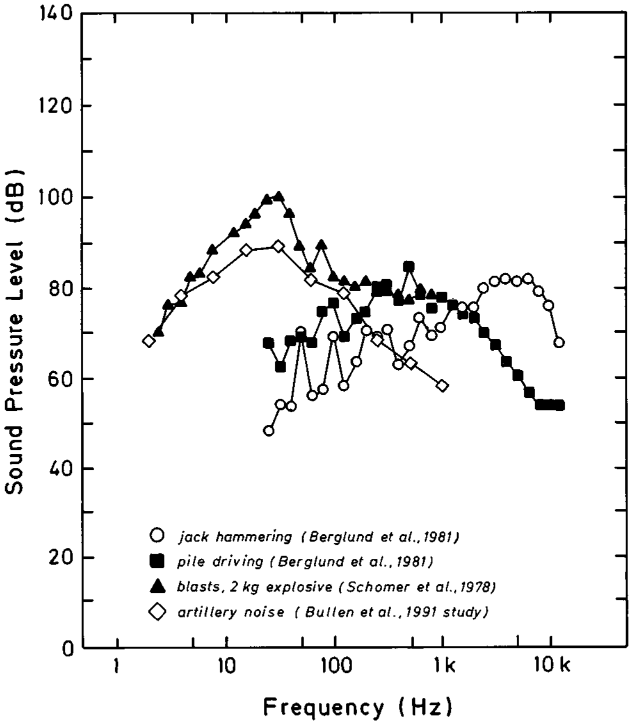

FIG. 4. Community noise exposure for impulsive sources as a function of frequency.

portation vehicles is shown in Fig. 3. The data presented in this figure indicate the extensive production of low-frequency noise by machinery, and especially transport machinery to which much of the population is exposed both inside the vehicles and while in proximity to the transportation corridor.

The data on impulsive noise sources are noteworthy because impulsive noise generates greater levels of subjective reactions such as annoyance and dissatisfaction than does nonimpulsive noise of the same energy level (Bullen *et al.*, 1991; Job, 1988; Schomer, 1981; Vos and Smoorenburg, 1985). The impulsive noise sources typically studied include quarry blasting (Fidell *et al.*, 1983; Murray and Avery, 1984), sonic booms (Kamperman, 1980; McKennel, 1978), explosions (Peploe *et al.*, 1993), and artillery (Bullen *et al.*, 1991; Schomer, 1981). Low-frequency noise exposures from various impulsive sources are presented in Fig. 4.

These data show that impulsive noise sources tend to differ from other community noise sources studied not only in their impulsiveness but also in their greater proportion of low-frequency noise. For example, the profiles of blast noise or artillery noise in Fig. 4 may be compared with the corresponding profile for road traffic noise (a commonly studied community noise) in Fig. 3.

A great proportion of low-frequency components of impulsive noises may, in part, account for a greater community reaction to some impulsive sources. The greater impact of impulsive noises with major components of low frequencies seems paradoxical, in that low frequencies themselves cannot be truly impulsive due to their long wavelengths. However, impulsive noise is a complex noise for which the time window for spectrum analysis is critical, and in addition, many impulsive sounds are fluctuating over time. Thus the present data analysis identifies a coincidence of impulsiveness and low-frequency noise in community sources rather than a physical necessity. Finally, the data on wind turbines indicate that the predominance of low-frequency noise is of particular concern for communities living close to wind turbines (Fig. 5). However, at distances of a few hundred meters the low-frequency noise is theoretically below hearing threshold.

The pervasive extent of low-frequency noise originating from machinery may result in it being experienced as a constant background noise (or so-called ambient noise), often at least partly masked by noise of higher frequencies. Figure 6 presents data on the spectrum of ambient noise in residential areas, in particular showing the magnitude of low-frequency noise in residential areas of Sydney, Australia.

Again, much but not all of the low-frequency energy is below hearing threshold (cf. Fig. 2). At times when the masking effect is reduced, due to, for example, the damping effect of walls in a building, which predominantly affects the higher frequencies, or during night time when surrounding noise is reduced, low frequencies will dominate the spectrum of perceived noise (Persson and Björkman, 1988). This is of particular concern because of the high proportion of the population who sleep at such times, and because of the evidence that sleep disturbance is of particular concern as an effect on human wellbeing (Berglund *et al.*, 1984).

Aircraft noise, a major source of community noise, also contains significant amounts of energy in the low-frequency range, as shown in Fig. 7. These data indicate that much of

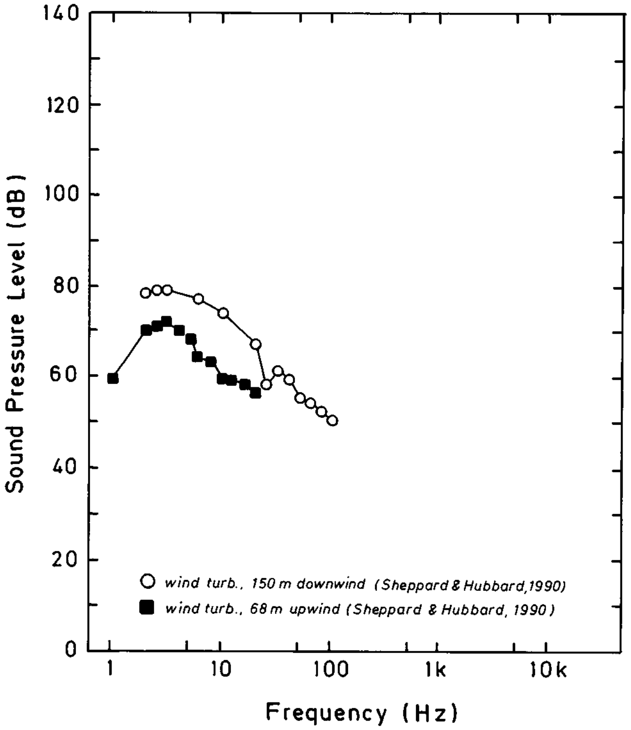

FIG. 5. Community noise exposure from wind turbines as a function of frequency.

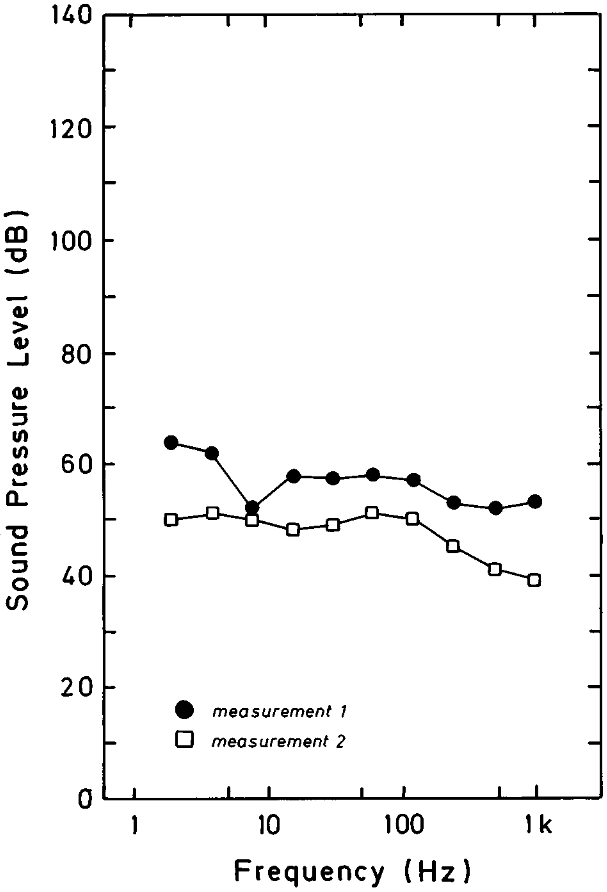

FIG. 6. Ambient noise levels as a function of frequency. The data were collected in residential areas (outdoors) around Sydney, as part of a study reported by Bullen *et al.* (1991). The two curves represent the background levels averaged over different measurement times at two different sites.

the low-frequency noise emanating from each of the aircraft-types recorded is audible.

In addition to general exposure to low-frequency noise (in the community and for passengers in many vehicles), substantial low-frequency noise exposure may occur at work. Figure 8 illustrates the noise spectra of air movement plants in various work environments, and identifies a predominance of low-frequency noise. Such machinery is common in many work environments other than those of heavy industry which are generally recognized to produce occupational noise problems. Thus occupational exposure to low-frequency noise may be more ubiquitous than first thought.

Transmission of low-frequency noise is noteworthy for several features which arise from its extremely long wavelengths. Low-frequency noise travels extended distances with very little energy loss. Dramatic examples attest to this claim: the sonic booms of supersonic aircraft flying between Europe and New York produce low-frequency noise levels as strong as 75 dB (Lin) as far away as the North of Sweden (Liszka, 1978); noise at 2 Hz apparently emanating from oil rigs in the North Sea also has been detected in Sweden (Liszka, 1974); low-frequency sound waves were recorded to travel around the earth several times after the volcanic eruption of Mt. Krakatoa; and a soundwave of 0.1 Hz will loose only 5% of its energy in traveling around the earth (see Backteman *et al.*, 1983a). The consequence of this feature is that even sources which produce noise energy evenly distributed across the frequency spectrum will result in relatively more and more of the energy of the noise occurring in the lower frequency range as the distance from the source increases. For example, Bryan (1976) recorded factory boiler noise at 18 and 46 m from the source. Noise in the 31-, 63-, and 125-Hz ranges in net suffered no detectable loss of energy between these two distances while noise in the 2-, 4-, and 8-kHz ranges each lost between 6 and 7 dB in propagation over the same distance.

The mismatch between the acoustical impedance of air and most objects, including the human body, prevents much of the sound energy from entering the ear. As the frequency of the wave is lowered, more of the energy enters the ear, the body, and other objects (von Gierke and Nixon, 1976). Thus low-frequency noise transmission extends into many objects allowing it to set up resonant vibration in our dwellings and our possessions as well as our chest cavities, sinuses, and throat.

III. PERCEPTION OF LOW-FREQUENCY NOISE AND VIBRATION

The relationship between frequency and sound-pressure level (SPL) is such that a sound with a frequency of 20 Hz has to exceed an SPL of approximately 84 dB (*re*: 20 μPa, i.e., relative to the international standard reference quantity, ISO R131, 1959; ISO 131, 1979) to be detected. For lower frequencies the SPL for detection must be higher. Figure 2 presented the results of a number of studies of hearing

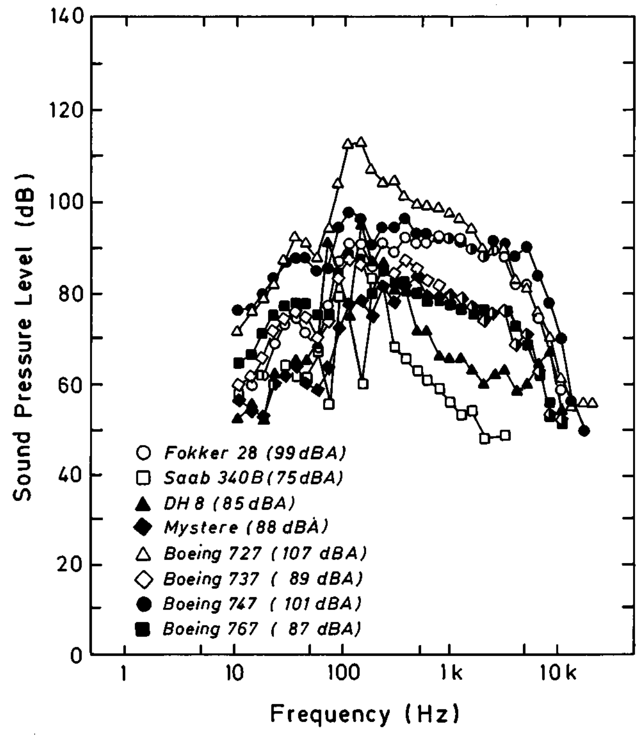

FIG. 7. Noise exposure as a function of frequency, for various aircraft types. These data are from recordings of aircraft movements taken outside, on the ground directly underneath the flight path, at Sydney Airport, Australia.

threshold for low-frequency noise and other noises. These research data show good agreement in supporting the following conclusions. First, low-frequency noise, including infrasound, is clearly detectable by the human auditory apparatus. Second, considerably more energy is required for detection in the low-frequency ranges. Finally, it should be noted that the absence of conscious (auditory) detection does not automatically mean that the noise has no other effects on the human body.

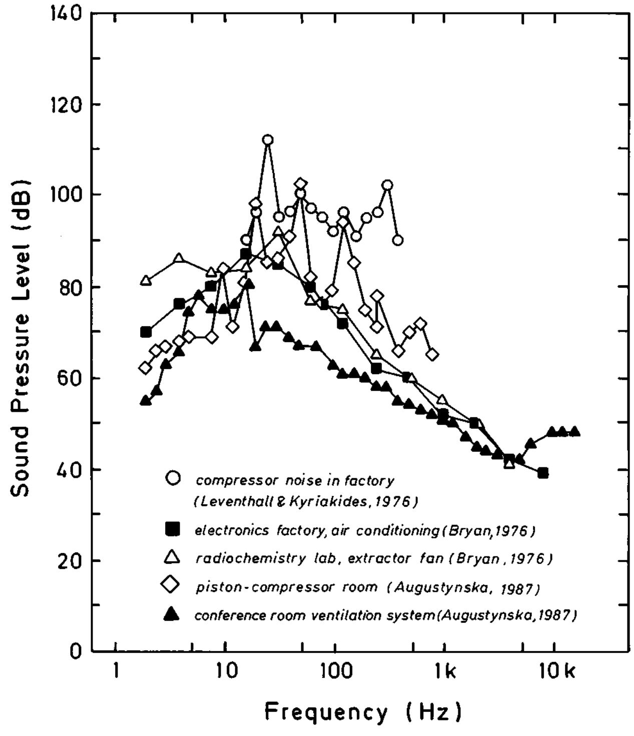

FIG. 8. Occupational exposure to noise from air movement plants.

A. Vibration

Humans are sensitive to vibration from a region below 0.5 Hz to at least 100 kHz, even though it is the region between 0.5 and 200 Hz that seems to cause most concern (Rao and Ashley, 1976). While most noise within the low-frequency range is perceived by the normal hearing system, vibration of the body also results from low-frequency noise and the surrounding area. This is an important source of stimulation which influences the human perception of, and reaction to, low-frequency noise. The consequences of these effects are considered further in relation to annoyance, below.

IV. MEASUREMENT OF LOW-FREQUENCY NOISE

A. Instrumentation

The physical means by which low-frequency noise is detected and calibrated have advanced considerably over the course of research interest in low-frequency noise, with the consequence that many of the earlier studies may be suspected of failing to control for a variety of confounding effects on the data reported. In particular, insufficient measurement and control of the frequency range and harmonics may be identified as potential problems in both field recordings and experimental generation of low-frequency noise. The digital technique that has revolutionized acoustic recordings of complex sound and their reproductions has contributed to the resolution of these difficulties.

B. Units of measurement

Sound-pressure levels are usually measured on a decibel scale (dB). Due to the complex function of the human auditory system, and the need to be able to assess sound-pressure level (the physical correlate of loudness) objectively and rapidly, different filters are therefore often used to weight sound-pressure values as a function of frequency. The filters were developed to approximate the supraliminal response characteristics of the human auditory system as determined from psychophysical experiments. The frequency weighting filters of sound-level meters are not based on the curve for the hearing threshold, but on equal-loudness or equal-annoyance contours. Such filters are standardized but it should be kept in mind that they are approximating the contours, and particularly so for low frequencies. Hence, the forms of the contours are uncertain due to lack of agreement in empirical data (e.g., Møller, 1987; Møller and Andresen, 1984). Thus in these filters, typically the midfrequencies are amplified in contrast to the low and high frequencies which are deemphasized. The presently used A, B, and C filters in sound-level meters were aimed at mimicking isoloudness curves over frequency under different conditions of sound intensities (Fletcher and Munson, 1933), that is, for sounds of low, medium, and high loudness level, respectively.

The reason for this is that the shape of these isoloudness contours varies with loudness level. An approximation of the Fletcher–Munson pure-tone pressure-field equal-loudness contour at 40 Phon is used in the A filter, at 70 Phon in the B filter, and at 100 Phon in the C filter. The measurement unit Phon is an equal-loudness metric that corresponds to dB SPL units for a pure tone centered at 1 kHz. The reason for introducing this unit is that the exponent of the underlying psychophysical power function relating (perceived) loudness to sound pressure varies with frequency. Unfortunately, most of the equal-loudness contours covering the low-frequency range (<70 Hz) are based either on nonempirical theoretical extrapolations and/or on sparse data that rely on uncertain methodology for comparisons over frequencies (Goldstein, 1994). As a special condition, the D filter was developed to account for aircraft noise (IEC 537, 1976). It is based on a new 40-Noy diffuse free-field contour obtained only for the frequency band range 50–11 200 Hz. At low frequencies it weights sound pressure similar to the B filter but amplifies it at high frequencies. The unit Noy was assigned to the perceived noisiness of a white noise band from 0.9 to 1.09 kHz at 40 dB SPL (Kryter, 1985, 1994). Within ''normal'' frequencies, the A filter appears to provide acceptable correlations between physical measures of noise and their corresponding subjective evaluations (e.g., Goldstein, 1994; Scharf and Hellman, 1980).

One major drawback with the scale of A-weighted SPL is, however, that it in fact underestimates the importance of frequencies below approximately 100 Hz (Kjellberg *et al.*, 1984; Kjellberg and Goldstein, 1985; Kuwano *et al.*, 1989). For example, loudness of noise which contains a substantial low-frequency component is underestimated by as much as the equivalent of 9 dB within the range 52–70 dB(A) (Gamberale *et al.*, 1982) or 6 Phon for 63 Hz and below (Berglund, 1990; Berglund and Berglund, 1986). In fact, for sounds exceeding an SPL of 60 dB, regardless of frequency, the reliability of the A-weighting diminishes (Berglund, 1990). Vercammen (1992) has suggested that an additional limit be set to the lower frequency part of the A-weighted spectrum (10–160 Hz) which lies 5–10 dB lower than the present one. The inability of A weightings to handle low-frequency noise is perhaps not surprising given that the isoloudness functions employed in the weighting were hand extrapolations into the lower frequencies rather than being based on empirical low-frequency data (see Goldstein, 1994). For example, in the absence of empirical data both Stevens (1975) and Kryter (1985, 1994) chose to extrapolate the equal-loudness and equal-noisiness contours into the low-frequency range.

Different procedures developed for predicting (perceived) loudness or annoyance of complex sounds from frequency weightings, or from various calculation procedures (e.g., Kryter, 1985, 1994; Zwicker and Fastl, 1990; Stevens, 1975), have been less successful for low-frequency noise. Bryan (1976) in his ''slope hypothesis'' suggested that spectrum shape, especially in the low-frequency range, should be considered. However, this hypothesis was later firmly refuted (Goldstein and Kjellberg, 1985).

In psychophysical terms, the perceived loudness of a pure tone at 1 kHz grows as a power function with sound pressure with an exponent of about 0.6 (Stevens, 1975). Exponents of the same magnitude have also been established for pure tones above 300–400 Hz (Marks, 1978). However, for a low-frequency tone of 20 Hz, the exponent is approximately twice as high, i.e., 1.2 (Goldstein, 1994). This indicates that a doubling in perceived loudness is achieved with only an increase of 4–5 dB for a low-frequency tone whereas a tone with higher frequency needs to be increased by 9–10 dB to elicit the same perception of a doubling in loudness (see Stevens, 1972; Whittle *et al.*, 1972).

An alternative approach to the determination of the appropriate measure of noise exposure is to examine the ability of various measures of noise to predict community reactions (dissatisfaction, and other factors in addition to annoyance: Job, 1993). Such different measures or indices take into account not only the frequency weighting but also special weighting for the event with maximum SPL, the number of noise events, time of the day, etc. (e.g., Goldstein, 1994). For example, Bullen *et al.* (1985; Job *et al.*, 1991) examined 88 different indices of aircraft noise exposure. Such studies of noise with a substantial low-frequency component have produced conflicting results. C weighting is recommended and commonly employed for artillery noise (e.g., Schomer, 1981) whereas Bullen *et al.* (1991) found that the unweighted level [24 h Leq dB(Lin)] provided slightly better prediction of reaction that did C weighting. The value of Zwicker's method of loudness calculation for noises of various spectral composition has been empirically confirmed (e.g., Berglund, 1990). In predicting reaction to blast noise from mining, Fidell *et al.* (1983) suggested that a complex measure based on centiles of the probability of ground vibration plus 10 Log (number of events) was a better predictor of reaction that equal energy units. However, subsequent reanalysis supported an equal energy unit as an effective predictor (Bullen and Job, 1985). While equal energy units have often proven the most effective predictor of community reaction (Bullen *et al.*, 1985; Bullen *et al.*, 1991; Job *et al.*, 1991), among presently available predictors, the issue of the best noise index for predicting reaction remains to be settled.

V. EFFECTS OF LOW-FREQUENCY NOISE ON HUMANS

The lack of attenuation of low-frequency noise by walls and other structures and its pervasive ambient levels make low-frequency noise a factor of critical importance to health (Møller, 1984). Because low-frequency noise is a major component of many occupational and community noises the effects of such noises may be viewed as, in part, the effects of low-frequency noise. The pervasively wide frequency mixture of real world noises renders the determination of pure low-frequency noise effects tenuous. The task is complicated by the more effective propagation of low-frequency noise which results in a changing mix of frequencies with distance from the source, and the more effective masking of higher frequency noises by low-frequency noise than vice versa (Wegel and Lane, 1924; Zwicker, 1963). Nonetheless, relevant data exist from two basic methodologies: laboratory studies of the effects of explicitly controlled noise exposures

TABLE I. Exposure parameters and results of TTS studies after exposure to low-frequency noise.

Reference	Exposure	TTS	Recovery
Alford *et al.* (1966; in Backteman *et al.*, 1983a)	119–133 dB 2–12 Hz 3 min	11 of 21 Ss had TTS (3–8 kHz) >10 dB (11–22 dB)	
Englund *et al.* (1978)	125 dB 14 and 16 Hz 2 h	TTS in 16-Hz condition for freq. between 125 and 1k Hz TTS max. 10 dB (250 Hz) No sign. TTS in 14-Hz cond.	
Jerger *et al.* (1966)	119–144 dB 7–12 Hz 3 min	11 of 19 Ss had TTS (3–6 kHz), TTS 10–22 dB	Within 30 min
Johnson (1973; in von Gierke and Parker, 1976)	126–171 dB 0.6–12 Hz 26 s–30 min	TTS in 140 dB; 4, 7, 12 Hz; 30-min condition (1 subject) TTS 14–17 dB	Within 30 min
		TTS for 1 of 8 Ss in 140 dB; 4, 7, 12 Hz; 5-min condition TTS 8 dB	Within 30 min
Mills *et al.* (1983)	octave band noise 84 and 90 dB 63, 125, 250 Hz 24 and 8 h	TTS in 84 dB; 63, 125, 250 Hz; 24-h condition TTS 7–15 dB TTS in 90 dB; 63, 125, 250 Hz; 8-h condition TTS 13–18 dB	Up to 48 h 12–24 h
Mohr *et al.* (1965)	discrete tones narrow-band noise 150–154 dB 10–20 Hz 2 min	No TTS after 1 h	
Nixon, 1973 (in von Gierke and Parker, 1976)	135 dB 18 Hz 5-min exposure in rapid succession	Average TTS of 0–15 after 30-min exposure	Within 30 min
Nixon (1973)	140 dB 14 Hz 5–30 min	TTS in 1 of 3 Ss. TTS 20–25 dB	Within 30 min
Tonndorf (in von Gierke and Parker, 1976)	Submarine diesel room 10–20 Hz, no level given	Depression of upper limits of hearing as measured by number of seconds a tuning fork was heard	In few hours outside of diesel room

and field studies of the effects of naturally occurring noise events. In addition, some studies have employed a combination of these methods, for example, by combining the home situation with controlled noise exposures (Peploe *et al.*, 1993).

Reviews of the health effects of noise in general exist (e.g., WHO, 1993), and are not repeated here. The review which follows is focused on laboratory studies which employ low-frequency noise, and on field studies of noise sources with a large low-frequency noise component.

A. Effects on hearing

Effects of low-frequency noise on hearing have been examined in terms of permanent loss of auditory acuity (permanent threshold shifts, PTS) and in terms of temporary threshold shift (TTS). While TTS is of less importance in itself (except for immediate performance which requires good auditory acuity), TTS may be viewed as the best average predictor of PTS (Ward, 1993). TTS is effective in predicting what noise sources will produce more PTS although it is not especially useful in predicting individual listener's losses (Ward, 1993). Thus, in considering losses induced by a source, such as low-frequency noise, TTS is of value. This predictor is a critical research tool because of the obvious problems involved in inducing PTS in research involving human beings.

1. Temporary threshold shifts (TTS)

A number of studies have examined TTS as a function of frequency of tones or narrow bands of noise. A compilation of results and exposure parameters of such studies concerned with low-frequency noise are summarized in Table I. These studies consistently show that TTS does occur with exposure to low-frequency noise, and the recovery period may be longer for sounds of higher pitch (Nixon and Johnson, 1973). However, the clinical significance of TTS is not clear since the exposure parameters employed are more extreme than those likely to actually be experienced in community noise. Nonetheless, these empirical data suggest the possibility of PTS resulting from occupational exposures, and leave open the possibility of PTS from sufficiently long durations of exposure in community settings.

B. Permanent threshold shifts (PTS)

For obvious reasons, data on PTS come from field studies of occupational exposure. Whereas such data focused on low-frequency noise are rare, a few studies of occupational noise sources with a large component of low-frequency noise exist. In addition, some early laboratory studies have employed exposures which would be unlikely to pass today's ethics committee's screenings of research: e.g., Mohr *et al.* (1965). Noise exposure in a submarine diesel room with a dominant frequency around 10–20 Hz produced TTS with recovery in a few hours (von Gierke and Nixon, 1976). Exposure to sonic booms resulted in no adverse effects on hearing even when exposure levels were intense (up to 6.9×10^3 N/m^2) or when continued for as much as 30 booms per day for two 30-day periods (for a review see von Gierke and Nixon, 1976). At extreme pressure (4.15×10^4 N/m^2) produced by very low-frequency noise, tympanic membrane damage may occur along with some inner ear damage (von Gierke and Nixon, 1976).

Given the common mix of frequencies in real world noises, the influence of low-frequency noise on the effects of energy in higher frequency bands should be considered. Consistent with the evidence that low-frequency noise is particularly effective in masking noise at higher frequencies, low-frequency noise may also ameliorate the hearing damage of higher frequency noise. Evidence for such an effect comes from Nixon's study of vehicle air bag inflation, in which reduced TTS occurred when low-frequency noise was added to a noise burst (see von Gierke and Nixon, 1976, pp. 130–131).

1. Aural pain

The threshold of aural pain is approximately 135 dB for sound energy around 50 Hz with a steady increase in threshold to around 155 dB at 5 Hz (von Békésy, 1960; von Gierke and Nixon, 1976).

C. Balance and the vestibular system

Intense energy in the very low-frequency ranges may affect the vestibular system. Because of ethical considerations and invasive measurement techniques much of the research on low-frequency noise and the vestibular system has been carried out on animal models, mainly monkeys and guinea pigs. Both species show evidence of vestibular effects of low-frequency noise in perilymph pressure (Parker, 1976). However, the behavioral significance of these responses is small given the absence of eye movement response associated with vestibular stimulation (nystagmus or counterrolling) to intense low-frequency noise (below 20 Hz) in both guinea pigs and monkeys (Parker, 1976). Parker's observations were made under exposure to intense stimulation (up to 172 dB). Overall the threshold of nystagmus was lower for higher frequencies, but still required intensities of 140 dB and above. This relationship between vestibular effects and frequency is consistent with the pattern for human subjects, and the absence of nystagmus in response to intense (up to 155 dB) low-frequency noise (0.6–12 Hz: see further von Gierke and Nixon, 1976). Thus vestibular effects appear to be greater for noise in the frequency range above 250 Hz.

D. Respiratory effects

Respiratory effects (suspended or reduced respiration, gagging, and coughing) of low-frequency noise have been documented in laboratory animals and human beings (von Gierke and Nixon, 1976). However, the intensity of stimulation required to produce such effects (150–154 dB) suggests that these effects are unlikely to be of practical importance except in extreme occupational exposure, such as might occur in rocket launches. Human accident data and animal data suggest a more extreme pressure limit for lung damage (1.05×10^5 N/m^2, according to von Gierke and Nixon, 1976).

E. Annoyance, loudness, and noisiness

The primary, and most frequently reported, perceived effect of low-frequency noise is not that of loudness or noisiness, but that of annoyance (Broner, 1978). The concept of annoyance is operationalized in various ways. It may refer to human response to noise events measured in laboratories, community studies of self-reported annoyance reactions, or the confusion of annoyance with disturbance of various activities such as conversation or sleep. The concept of noisiness has been used sometimes synonymously with annoyance (Kryter, 1985, 1994) and sometimes as a quality characteristic of sounds (Berglund *et al.*, 1975).

The degree of annoyance or disturbance generated by a specific noise, regardless of frequency, is difficult to predict accurately for individuals (Haslegrave, 1990; Job, 1988). The same noise may for different people result in totally different responses depending on cultural factors (Kuwano *et al.*, 1991), activity at the time of exposure (Borsky, 1980), attitude to the noise source (Fields, 1992, 1993; Job, 1988), noise sensitivity (Job, 1988; Stansfeld, 1992), controllability of the stressor (Evans, 1982), and other individual differences (see Job, 1993). Prediction of individual reactions is also slightly limited by the reliability of the reaction and noise measures (Job, 1991). Nonetheless, prediction of the averaged reactions of groups of subjects in socioacoustic surveys is good (Job, 1988).

Scales of the perceived loudness, noisiness, and annoyance of noises generally show strong correlations (Berglund *et al.*, 1986; Peploe *et al.*, 1993; Stevens, 1961, 1972), although the three scales do dissociate with more complex sounds or examination of stimuli which differ on a number of characteristics such as rise time, sharpness, spectral content, information content (Berglund *et al.*, 1975, 1976; Berglund *et al.*, 1994a; Berglund *et al.*, 1994b; Hellman, 1984;

Preis and Berglund, 1993), or contextual effects such as the task being undertaken at the time (Lindvall and Radford, 1973).

Low-frequency noise differentiates itself from noise that consists of a broader frequency spectrum in that it seems more difficult to predict both loudness and annoyance accurately. Even though the A filter has proven itself useful as an approximate estimation of annoyance for mid- to high-frequency stationery noise, it severely underestimates annoyance as well as (perceived) loudness when the noise contains low-frequency components. Bryan (1971, 1976), for example, found that noise containing high levels of low-frequency noise, and low levels of high-frequency noise, gave rise to vigorous complaints even though the exposure level was only around 55 dB(A). Tempest (1973), investigating low-frequency noise present in a car, a diesel train, from traffic noise indoors, an oil furnace, and from a ventilation installation, found that the number of complaints were far larger than could be predicted from the sound-pressure levels of the noises as judged by the dB(A) level. Similarly, Persson and Björkman (1988) compared four broadband fan noises centered at 80, 250, 500, and 1000 Hz and found that the 80-Hz band was perceived to be significantly more annoying than the other noises at equal A-weighted levels. A considerable body of research has produced similar findings (e.g., Broner and Leventhall, 1978, 1982; Gamberale *et al.*, 1982; Goldstein and Kjellberg, 1985; Kjellberg *et al.*, 1984; Persson *et al.*, 1985, 1990; Persson and Rylander, 1988; Scharf *et al.*, 1977; Vasudevan and Leventhall, 1982, 1989; Åkerlund *et al.*, 1990).

Comparison of socioacoustic survey results from different noise sources also supports a greater reaction (for equal loudness) to sources with more low-frequency components. Reaction to aircraft noise is generally higher than reaction to road noise, and this difference has been identified in direct comparison within a single study (Hall *et al.*, 1981).

Low-frequency noise also differs from other noise in producing vibrations of the human body and other objects. This is of practical significance to human reactions to the noise. For example, the extremely intense low-frequency noise produced by aircraft during takeoff (see Fig. 7) may rattle doors, windows, and other household objects, thereby causing discomfort and annoyance reactions. Rattle and vibration magnify reaction to the noise (Berglund *et al.*, 1975; Bullen *et al.*, 1991; Howarth and Griffin, 1991; Schomer and Neathammen, 1987; WHO, 1993). This effect is of significant size. Schomer and Averbuch (1989), investigating noise from helicopters and artillery which produce blast sounds containing little energy above 200 Hz, found that no commonly used environmental noise measure could adequately describe the indoor environment in cases when the blast excited rattles. Even though extremely small (under 1 dB) changes in both A- and C-weighted SPL were registered, subjective response changes equal to noise of up to 13 dB occurred when the blast excited rattles. Finally, in a multiple regression application to predict overall reaction (dissatisfaction) to artillery noise, reaction to the shaking and vibration was found to be a better predictor than all the disturbances of activities (conversation, watching television, reading, relaxing, etc.) combined (Bullen *et al.*, 1991). The effects of vibration of the human body on reaction are complicated by tendency to confuse vibration emission with noise alone, whereby people ''hear'' more noise than is actually present (e.g., Griffin, 1990; Howarth and Griffin, 1990; Kastka and Paulsen, 1991; Kryter, 1985, 1994). The opposite is also possible: Motion sickness has been linked to low-frequency noise even without accompanying vibration (Yamada *et al.*, 1991).

Another particular feature of low-frequency noise is that it is often accompanied by a throbbing characteristic which may increase the annoyance reactions (Broner and Leventhall, 1983; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982, 1989).

F. Nonauditory physiological effects

1. Cardiovascular effects

Laboratory studies of noise at various frequencies show noise-induced changes in blood pressure with vasoconstriction or vasodilation, and heart rate change (e.g., Andrén, 1982; Andrén *et al.*, 1988; Andrén and Hanson, 1983; Carter and Beh, 1989; Osada *et al.*, 1972; Parrot *et al.*, 1992; Rovekamp, 1983; Vallet *et al.*, 1983). However, these effects interact with task demands (Tafalla and Evans, 1993); they are not uniformly observed (Etholm and Engenberg, 1964) and are of unclear clinical significance. Nonetheless, the observation that those with a family history of hypertension show more pronounced cardiac reaction to noise is indicative of concern (von Eiff *et al.*, 1981). The finding that men show more reaction than women (Loeb *et al.*, 1982; Yamada *et al.*, 1986) also adds weight to the clinical relevance of the reactions given that men, on average, suffer cardiac infarction earlier than women.

Studies of low-frequency noise specifically have shown changes in heart rate in subjects who suffer from low-frequency noise, but not in other subjects (e.g., Yamada *et al.*, 1986). This pattern of results suggests that reactions to low-frequency noise may not have habituated in these subjects or that the habituation is specific to the environment in which the noise exposure occurs, consistent with a classical conditioning theory of habituation (Hall and Honey, 1989; Lovibond *et al.*, 1984). Extending the lack of habituation, Michalak *et al.* (1990) showed a sensitization effect in response to aircraft noise.

Long-term exposure appears to produce peripheral vasoconstriction with occupational (Zhao *et al.*, 1991) or other exposure (Neus *et al.*, 1983). Children living under the flight paths in Los Angeles also show elevated blood pressure (Cohen *et al.*, 1986). Adults living in highly exposed road noise areas showed slight increases in heart disease risk (Babisch *et al.*, 1993) while those in highly exposed aircraft noise areas showed elevated blood pressure, greater use of blood pressure medication and greater prevalence of cardiovascular disease (Knipschild, 1977a, 1977b, 1980; Knipschild and Oudshoorn, 1977). The latter studies included tracking across time to show that with a change in the aircraft operations blood pressure medication changed accordingly. The latter result suggests that these effects may be attributed to the noise rather than self-selection of the relevant populations or other differences between the areas under comparison. Clearly, long-term high blood pressure may be of clinical significance (Jansen, 1969; Hattis *et al.*, 1980).

Although health effects of noise have been extensively researched (see, e.g., Berglund and Lindvall, 1990; Berglund *et al.*, 1990; Vallet, 1993), no study has specifically compared complex low-frequency noise with other complex noises to determine if there is differential reaction. However, circulatory system effects of low-frequency noise have been identified in the laboratory and the studies of aircraft noise are of particular relevance by virtue of their high proportion of low-frequency noise. For this reason, particular health concern should be given low-level military aircraft which will produce intense exposure. It would appear on balance of probability that low-frequency noise produce cardiovascular effects.

2. Endocrine effects

Laboratory studies show increased catacholamines and cortisol in response to noise (e.g., Cantrell, 1974; Cavatorta *et al.*, 1987; Welch and Welch, 1970). As with other stressors, the effects of controllability may affect endocrine reactions to noise (Averill, 1973; Job, 1993; Lundberg and Frankenhaeuser, 1978). These hormonal changes, if prolonged, may produce significant health-related effects (decreased immunity, increased heart rate and blood pressure, and cardiac arrhythmias). A review by Bly *et al.* (1993) suggested that there is evidence of immunomodulation by noise stress. The effects of frequency spectrum of the sound are not known.

G. Effects on performance and cognition

Effects of noise on performance have been intensively investigated and reviewed (Abel, 1990; Broadbent, 1957; Davies and Jones, 1985; Jones, 1984; Loeb, 1981). While noise clearly affects performance on a variety of tasks, especially divided attention tasks, the effects often interact in complex and inconsistent ways with time of day, arousal, and gender (Frankenhaeuser and Lundberg, 1977; Hamilton and Hockey, 1970; Holding *et al.*, 1983; Salamé, 1988), and with task speed and accuracy (Broadbent, 1954; Carter and Beh, 1987). Importantly, the learning of children is also affected by noise (Evans, 1990; Hygge, 1993).

Despite this extensive and sophisticated research literature, studies of the effects of low-frequency noise are surprisingly rare and inferences can only be drawn from predominantly low-frequency noise. For example, drivers of heavy lorries experience a reduction in wakefulness which can be attributed to low-frequency noise (Landström *et al.*, 1988). Thus, to date, there is no clear evidence to suggest that low-frequency noise has differential effects on performance or cognition.

H. Sleep disturbance

Sleep disturbances and poorer performance due to sleep loss have been reported when either continuous or intermittent noises were present (Eberhardt *et al.*, 1987; Thiessen, 1970, 1978). This has been verified by questionnaires (e.g., Langdon and Buller, 1977) and through laboratory studies in which noise of various SPLs have been alternated with quiet nights (Carter *et al.*, 1993a; Jurriens *et al.*, 1983; Thiessen and Lapointe, 1978, 1983; Wilkinson *et al.*, 1980; Öhrström and Rylander, 1982). It should be noted that sleep disturbance is also an effect of ongoing concern in daytime noise, because of shift workers (see Carter *et al.*, 1993b; Knauth and Ruthtranz, 1975).

Noise produces cardiovascular effects during sleep (Muzet and Ehrhardt, 1978; Muzet *et al.*, 1981); changes in sleep pattern (e.g., Wilkinson and Campbell, 1984) and sleep loss appear to cause compromised immunity (Brown, 1991; Brown *et al.*, 1989; Palmblad *et al.*, 1976; Palmblad *et al.*, 1979). Thus it is of significance not only because of the disturbance at the time but also because of health-related changes.

Although the effects of noise on sleep are well documented (see Öhrström, 1993a), studies of low-frequency noise are again rare. A relevant exceptional study is that by Nagai *et al.* (1989). They described how inhabitants living along a superhighway initially complained of the shaking and rattling of windows, then became chronically insomniac and excessively tired from the continuing low-frequency noise reaching levels between 72 and 85 dB(A). It is apparent that low-frequency noise disturbs sleep, and when it produces rattle it is likely to be more disturbing than higher frequency noise.

I. Effects on communication and psychosocial effects

There can be no doubt that noise can mask speech. However, the degree depends on a number of factors of the speech and the masking noise. In principle, noises around the same frequency as speech (mainly between 0.1 and 6 kHz) will mask more effectively than noise at higher frequencies. However, given the upward spread of masking which makes low-frequency noise an efficient masker of noises of higher frequency, low-frequency noise can be expected to mask speech rather well. In support of this supposition, intense noise of frequencies as low as 20 Hz has been found to affect speech intelligibility adversely (Pickett, 1959). This effect appears to be ignored in the development of methods utilized to predict speech intelligibility. For example, the articulation index (French and Steinberg, 1947; Kryter, 1962), the speech interference level (Beranek, 1947; see also ANSI, 1969), the rapid speech transmission index (see Houtgast and Steeneken, 1983), and direct measurements of SPL, in dB(A) (Klump and Webster, 1963; Kryter, 1985, 1994; Loeb, 1986), have been used to predict speech interference level. These measures cover the region between 250 and 7000 Hz which, admittedly, covers the range for the human voice. Common to all these methods is that they do not consider the upward spread of masking by low-frequency noise.

The factors of annoyance with speech interference are more complex than those of the interference itself, and encompass cognitive factors apparently unrelated to low-frequency noise (see Bergman, 1980; Miller and Licklider, 1950; Preis and Terhardt, 1989). However, noise may under certain exposure conditions result in better speech intelligibility due to the process of auditory inclusion and thus also reduce its effect on annoyance reaction (Berglund *et al.*, 1994a).

A number of nondesirable social effects have been found in connection with living in noisy neighborhoods, such as an increased crime rate and decreased casual social interaction (Appleyard and Lintell, 1972). The latter effect may, however, be more a result of impaired speech communication due to masking than from noise *per se*. Noise may also affect the act of helping. Specifically, subjects have been shown to offer less help with various tasks in the presence of noise as compared to the same situation without the noise (Boles and Hayward, 1978; Page, 1977). Generally, broadband community noise, including low-frequency noise, may even at low levels constitute a risk for certain groups such as the elderly, the hearing impaired, and children at the stage when they acquire language (WHO, 1993).

J. Mental health

Like so many outcomes, the effects of noise on mental health are difficult to establish because of confounding differences between populations exposed or not exposed to noise. For example, studies of populations near versus not near Los Angeles Airport were confounded by differences in racial composition among other factors (Meecham and Shaw, 1979; Meecham and Smith, 1977). However, long-term studies suggest a complex relationship between mental health effects such as depression, noise sensitivity, and noise exposure (Stansfeld, 1992; Stansfeld *et al.*, 1985). Other long-term studies have identified the possible effects of noise on psychosocial well-being (Öhrström, 1993b). Furthermore, Kryter's (1990) reanalysis of psychiatric hospital admission rates identified an effect of aircraft noise independent of confounding factors which were statistically or selectively controlled.

Examination of mental health effects of pure low-frequency noise is not feasible since pure sources occur rarely in the real world. However, the effects of aircraft noise (which contains much low-frequency energy; see Fig. 7) outlined above are consistent with a role of low-frequency noise in mental health effects. The possibility that mental health effects grow in part from annoyance and feelings of helplessness (Job, 1993; Job and Barnes, 1995; Overmier and Hellhamer, 1988; Seligman, 1991) and the greater annoyance occasioned by low-frequency noise are suggestive of greater effects from low-frequency noise than from other noises.

VI. METHODOLOGICAL ISSUES

In determining the effects of low-frequency noise on human well-being a myriad of methodological issues arise. Because the problems differ between the various basic research methods, these are listed below separately for the laboratory and field studies.

A. Laboratory studies

(1) The standard methodological issues to do with selection of subjects, experimenter bias and all the complex effects of context (including stimulus range, regression, and sequential order effects) are relevant to laboratory studies of noise in general and of low-frequency noise in particular. These effects have been critically reviewed elsewhere (Goldstein, 1994; Poulton, 1989). The impact of these effects may be reduced by master scaling which is a procedure by which individual differences in perceptual scaling are utilized for obtaining calibrated scales, independent of exposure context (Berglund, 1991).

(2) Examination of low-frequency noise in the laboratory requires its generation or reproduction and presentation to the subjects. Problems have, for example, included impure signal, insufficient air space in headphones, and the generation of harmonics (see von Békésy, 1960; Yeowart, 1976). These problems have been steadily reduced with advances in technology and knowledge.

(3) Measurement of low-frequency noise has also proven difficult. Tolerances in sound-level meters have been much more lenient for low-frequency noise (e.g., Brüel & Kjær, type 2209.3: IEC, 1979). Technical concerns with the capture of low-frequency noise have been reviewed (Goldstein, 1994) and measurement unit problems were considered earlier.

(4) Doubts about the generalizability of laboratory findings to real world situations apply particularly to research on low-frequency noise. For example, the effects of the unfamiliar laboratory environment on noise-induced sleep loss are difficult to establish. Even studies which allow some nights of familiarization to the sleeping laboratory may not replicate the effects of years of sleeping in the same room. The observations may also involve classic Hawthorne effects (cf. Dickson and Roethlisberger, 1966). Similarly, studies of annoyance in the laboratory may overlook the effects of ameliorating actions in one's home, such as turning up the volume of the television or radio sets. Another reaction of importance here is habituation which may be specific to the environment in which the noise is heard (Hall and Honey, 1989; Lovibond *et al.*, 1984), which will result in an absence of habituation in the laboratory. Related research on the creation of positive sound environments may provide answers here. Studies which combine the experimental and field methods in examining, for example, sleep disturbance in the home and annoyance from controlled exposures in the home (Peploe *et al.*, 1993) are helpful in this regard.

(5) Generalization from temporary effects to clinical significance is uncertain for many effects, although in the cases of TTS, mental illness, and blood pressure, there is somewhat more reason for confidence.

(6) The earliest studies employed exposure levels which would almost certainly not be allowed today. While these data are therefore of value, these studies apparently employed inadequate data collection via insufficient self-report (Mohr *et al.*, 1965).

(7) The early experiments were often conducted on military subjects who had participated in many experiments and so received much noise exposure. The effects of this prior experience are unknown.

B. Field studies

(1) Field studies of the effects of noise including low-frequency noise run the same risks in methodology as field studies in general (e.g., Last, 1988). These include problems with drawing causal inferences from correlational data obtained in cross-sectional studies or from one aggregate level to another (ecological fallacy), the use of self-report data from respondents who may be motivated to exaggerate their reactions, confounding differences between populations exposed or not exposed to noise, biases from certain types of people agreeing to participate versus those who refuse or are not home when the study is done, interviewer bias, and question wording bias. Some of these problems are relieved in studies of noise by multiple calls back to residences producing high response rates (e.g., Hede and Bullen, 1982), or by group questionnaire administration (e.g., Job and Bullen, 1987), or by other means (see Job and Bullen, 1985). Nonetheless, problems remain to be resolved.

(2) The extrapolation from observed effects to clinical significance is not as critical a problem as in laboratory studies, but remains a problem nonetheless for some measures. Although of significance in itself, it is not clear whether annoyance created by low-frequency noise leads to other mental health problems, nor whether reduced psychosocial well-being in high noise areas is a predictor of more serious mental disorders.

(3) Respondents may have difficulty identifying the source of low-frequency noise and so may misattribute the noise to another source in reporting their reactions (cf. Berglund, 1991; Berglund *et al.*, 1980).

(4) Perhaps the most serious problem specific to field studies of low-frequency noise is that pure low-frequency noise is rare. Thus most such studies are of broadband noise with a predominant or significant low-frequency component. Thus the effects of low-frequency noise *per se* are difficult to identify. Comparison of different noise sources with differing components of low-frequency noise is only a partial solution to this problem. The different noise sources differ on many variables in addition to their low-frequency components. For example, attitudes to the noise source, time of day of noise, proximity, and visibility of the source may all vary and may all affect reaction.

VII. ABATEMENT OF LOW-FREQUENCY NOISE

With the automation of technological processes in industry, an increasing number of workers are moved from the immediate vicinity of the machinery to control cabins of some sort. These cabins offer the opportunity to reduce noise hazards, vibration, and other harmful agents in the working environment. The sound insulation ability of ‘‘soundproof’’ cabins averages typically 30–50 dB for frequencies above 500 Hz, but only 0–19 dB for frequencies below 500 Hz (Kaczmarska and Augustynska, 1992). Thus their ability to reduce low-frequency noise is less than adequate. Likewise, the use of personal hearing protectors is less effective in the low-frequency range. For example, Harris (1979) has shown that the use of earplugs alone may reduce the noise level by as much as 40 dB within the frequency range 800–8000 Hz. If earplugs are used in combination with earmuffs, a reduction of up to 60 dB can be obtained. The same protectors may, however, only reduce the low-frequency noise (within the range 20–100 Hz) by about 5–25 dB (Harris, 1979). This form of local protection also fails to address effects of low-frequency noise on other parts of the body. Thus personal hearing protectors are not the ideal solution for low-frequency noise.

Transmission loss through walls and windows are lower within the low-frequency region than for noise of higher frequencies, especially if the room resonances coincide with the low-frequency noise (Leventhall, 1988). However, with double glazing, attenuation can be achieved, as shown in the middle panel of Fig. 9. The general difficulty of insulating against low-frequency noise highlights the value of attenuation of the noise at the source, as suggested, for example, by Backteman *et al.* (1983a, 1983b), rather than allowing the noise to spread.

Figure 9 shows the results of three sound abatement studies which considered a range of frequencies of noise including low-frequency noise. The left panel shows a successful source reduction. Another successful case is described by Ellison (1991) in which a large rope-making machine together with a number of smaller machines were found to cause what the complainant described as a ‘‘throbbing noise.’’ However, in this case, the disturbing noise was propagated through ground-borne vibrations in the range 8–13 Hz. The solution was to improve the maintenance of the machines which led to a reduction of vibrations and noise in the range 15–20 dB. This reduction satisfied the complainant, and as a side effect improved the serviceability of the machines in question.

Active noise control is a viable alternative to passive attenuation especially with respect to ventilation and exhaust fan noise (Wise *et al.*, 1992). Active attenuation preserves the unobstructed airflow by injecting canceling noise into the duct. The technique is particularly efficient for low-frequency noise which may be reduced by 3–18 dB depending on frequency composition (Leventhall *et al.*, 1994). Additional advantages of active control are that external lagging of ducts is not necessary, a thinner sound absorptive lining may be used inside for attenuation of high-frequency noise, and the running costs of the active system may be as low as 1% of the energy saved by reduced airflow resistance compared to a corresponding passive attenuation system.

VIII. RECOMMENDATIONS

A. Research needs

Further research is needed in relation to a number of features and outcomes of low-frequency noise. These needs include the following.

(1) In general, there has been too little research on the role of different frequency spectra of noise in the production of effects on humans. Greater consideration of this factor in many studies of noise is desirable.

(2) Most of the research of adverse effects of low-frequency noise in humans has used short durations of exposure. It is of great importance to research prolonged expo-

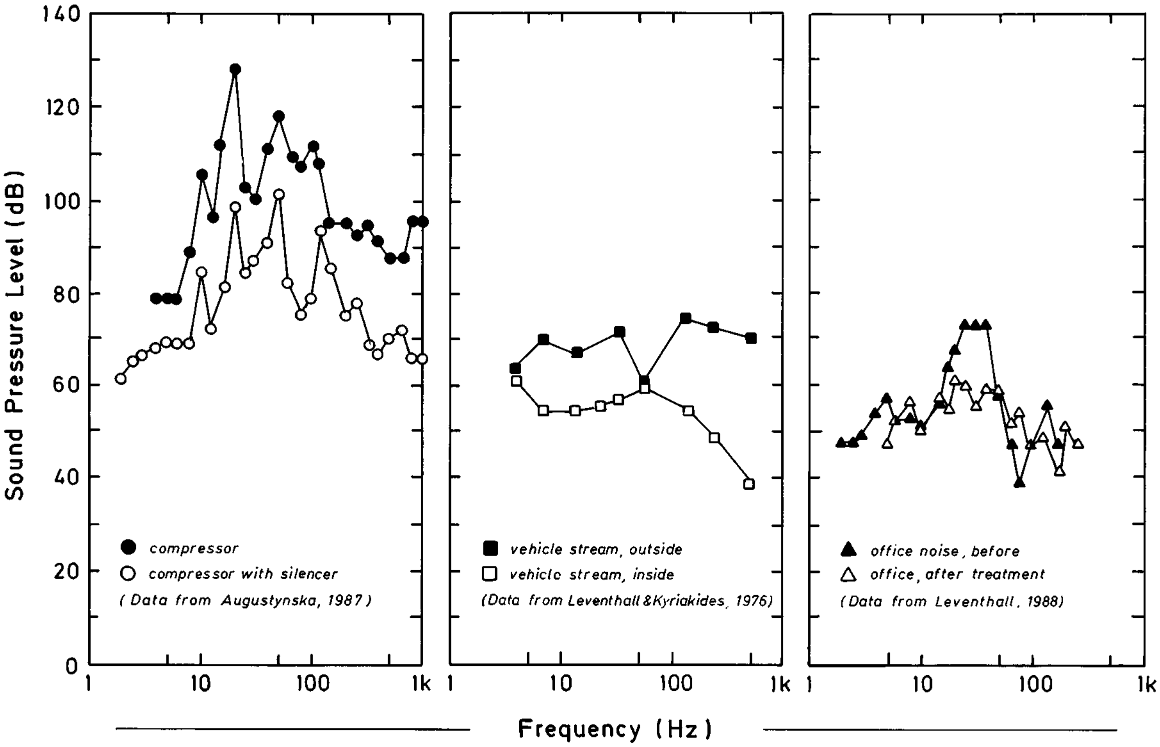

FIG. 9. The results of three low-frequency noise abatement studies.

sures, extending at least over 15–30 min, so that the effects may be generalized from laboratory studies to field situations.

(3) Longitudinal studies of the effects of low-frequency noise sources are needed in order to examine the long-term pattern of effects (see also Berglund *et al.*, 1984). At this stage the pattern of development of and possible predictors of problems of clinical significance are unclear. Predictors of later problems would be of value in providing prophylactic interventions instead of treatment after the problem is established.

(4) Noise sources sometimes change substantially, such as in changes to road traffic with openings of new freeways or aircraft traffic with new airports or runways. Such occasions provide relatively rare opportunities to assess the effects of noise to a large extent independent of the effects of population differences arising from selection of living location in quiet or noisy areas. Such opportunities should not be missed, and in such studies the frequency spectrum of the noise should be assessed.

(5) Given the impure examples of low-frequency noise which exist for field studies, comparison of different sources is necessary to provide a guide as to the contribution of low-frequency noise to the reactions observed. However, such comparisons are confounded by other differences between the sources. These differences could largely be handled by measurement of these factors and statistical control of them.

(6) The mechanisms of individual differences in the effects of noise are of critical concern. Examination of which individuals are most affected and what features they share is needed. Knowledge of the mechanisms of these effects may be invaluable in intervening to prevent the adverse effects of low-frequency noise.

(7) The impact of environmental noise with low-frequency components should be researched for various risk groups such as persons with impaired hearing, noise sensitive individuals, children who develop learning disabilities, the elderly (with presbyacusis), etc. Knowledge of effects on such populations is of particular concern because of the prevalence of low-frequency noise in indoor sources such as ventilation systems.

(8) The development of standardized techniques to measure low-frequency noise in the laboratory, in housing, and at work sites is desirable. The inadequacy of weighting filters in sound-level meters has been identified.

(9) Laboratory studies of the effects of the various features of (real and artificial) noise signals are needed.

(10) The relative contributions of low-frequency and impulsiveness and tonal aspects of noise require further examination in laboratory and field studies.

(11) Detailed assessment is needed of the relative importance of vibration and rattle versus the low-frequency noise itself in producing reactions. This would involve both laboratory and field research.

(12) Continued development of methods for low-frequency noise attenuation and control measurement technology are needed.

B. Action on the basis of current knowledge

The effects of low-frequency noise (and many other environmental pollutants) on human beings are difficult to establish for various methodological reasons outlined above. Definitive solutions to these problems would require unethical exposures to low-frequency noise. Thus the effects must be judged on balance. The balance of probability would appear to favour the conclusion that low-frequency noise has a variety of adverse effects on humans, both physiological and psychological. These latter effects are often more serious than those produced by higher frequency noise, partly due to the pervasiveness of low-frequency noise, its efficient propagation, and reduced efficacy of many structures in attenuating low-frequency noise. The evidence provided in this review warrants concerned action without the potentially extremely lengthy delay that may be occasioned by waiting for definitive proof which may never arise.

In industrial and community settings more emphasis should be placed on determining the frequency spectrum of a noise rather than the current focus on sound-pressure level alone. Some standards for industry allow greater exposure to low-frequency noise, possibly on the basis that much of it cannot be heard. For example, the Polish standards allow more noise in the range below 20 Hz than in higher frequencies (see Kaczmarska and Augustynska, 1992). Such standards should consider the option of allowing less noise in the low-frequency range since the possibility exists that a stimulus may have an effect even without conscious (auditory) detection.

Low-frequency noise emission can often be reduced through insulation of the source, better maintenance of relevant machinery (e.g., ventilation ducts) or active sound absorption (see Gan, 1987; Leventhall *et al.*, 1994). Such measures should be actively encouraged.

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