A Review of Published Research on Low Frequency Noise and its Effects

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1. Preamble

Low frequency noise causes extreme distress to a number of people who are sensitive to its effects. Such sensitivity may be a result of heightened sensory response within the whole or part of the auditory range or may be acquired. The noise levels are often low, occurring in the region of the hearing threshold, where there are considerable individual differences. There is still much to be done to gain a fuller understanding of low level, low frequency noise, its effects, assessment and management. Survey papers of low frequency noise and its occurrence include (Backteman et al., 1983a; Backteman et al., 1983b; Backteman et al., 1984a; Backteman et al., 1984b; Berglund et al., 1996; Broner, 1978a; Hood and Leventhall, 1971).

Historically, early work on low frequency noise and its subjective effects was stimulated by the American space programme, a source of very high levels of low frequency noise. The launch vehicles produce their maximum noise energy in the low frequency region. Furthermore, as the vehicle accelerates, the crew compartment is subjected to boundary layer turbulence noise for about two minutes after lift-off. Experiments were carried out, in low frequency noise chambers, on short term subjective tolerance to bands of noise at very high levels of 140 to 150dB in the frequency range up to 100Hz It was concluded that the subjects, who were experienced in noise exposure and wearing ear protection, could tolerate both broadband and discrete frequency noise in the range 1Hz to 100Hz at sound pressure levels up to 150dB. Later work suggests that, for 24 hour exposure, levels of 120-130dB are tolerable below 20Hz. These limits were set to prevent direct physiological damage (Mohr et al., 1965; von Gierke and Nixon, 1976; Westin, 1975). It is not suggested that the exposure was pleasant, or even subjectively acceptable, for anybody except those who might have had a personal interest in the noise. The levels used in the experiments are considerably higher than the exposure levels of people in their homes, arising from environmental, traffic, industrial and other sources.

The early American work was published in the mid 1960's and created no great sensation, but a few years later infrasound entered upon its "mythological" phase, echoes of which still occur. Infrasound – the "silent sound" - was blamed for many misfortunes for which another explanation had not yet been found (e.g., brain tumours, cot deaths, road accidents). A selection of some press headlines from the early years is:

- *The Silent Sound Menaces Drivers - Daily Mirror, 19th October 1969*
- *Does Infrasound Make Drivers Drunk - New Scientist, 16th March 1972*
- *Brain Tumours 'caused by noise' - The Times, 29th September 1973*
- *Crowd Control by Light and Sound - The Guardian, 3rd October 1973*
- *Danger in Unheard Car Sounds - The Observer, 21st April 1974*
- *The Silent Killer All Around Us - Evening News, 25th May 1974*
- *Noise is the Invisible Danger - Care on the Road (ROSPA) August 1974*

Blatantly incorrect claims were made in the book 'Supernature' by Lyall Watson, first published in 1973 as 'A natural history of the supernatural' and which had large sales as a paperback. For example, it stated that, in an experiment with infrasonic generators, all the windows were broken within a half mile of the test site and further, that two infrasonic generators "focused on a point even five miles away produce a resonance that can knock a building down as effectively as a major earthquake".

Those who were investigating low frequency noise problems at this time were often asked "It's dangerous, isn't it?" Public concern over infrasound was one of the stimuli for a growth in complaints about low frequency noise during the 1970's and 1980's and may still have lingering effects.

However, infrasound has long been a respected area of study in meteorology, where the frequencies range from as low as one cycle in 1000 seconds up to a few cycles per second. Large arrays of infrasound microphones detect low frequencies originating in atmospheric effects, meteorites, supersonic aircraft, explosions etc. There is also a worldwide system of about 60 infrasound arrays, which are part of the monitoring for the Nuclear Test Ban Treaty.

It is a big step from the American endurance exposures and the exaggerated effects of infrasound to the very real low frequency noise difficulties faced in a number of environmental noise problems, where low frequency noise occurs at low levels, often in the region of an individual's hearing threshold. The noise, typically classed as "not a Statutory Nuisance", causes immense suffering to those who are unfortunate to be sensitive to low frequency noise and who plead for recognition of their circumstances.

The World Health Organization is one of the bodies which recognizes the special place of low frequency noise as an environmental problem. Its publication on Community Noise (Berglund et al., 2000) makes a number of references to low frequency noise, some of which are as follows:

- *" It should be noted that low frequency noise, for example, from ventilation systems can disturb rest and sleep even at low sound levels"*
- *"For noise with a large proportion of low frequency sounds a still lower guideline* (than 30dBA) *is recommended"*
- *" When prominent low frequency components are present, noise measures based on A-weighting are inappropriate"*
- *"Since A-weighting underestimates the sound pressure level of noise with low frequency components, a better assessment of health effects would be to use C-weighting"*
- *"It should be noted that a large proportion of low frequency components in a noise may increase considerably the adverse effects on health"*
- *"The evidence on low frequency noise is sufficiently strong to warrant immediate concern"*

This present study considers some properties of low frequency sounds, their perception, effects on people and the criteria which have been developed for assessment of their effects. Proposals are made for further research, to help to solve the continuing problems of low frequency environmental noise.

2. Introduction to the physics of low frequency noise

2.1 **Noise and sound.** Noise and sound are physically the same, differences arising in their acoustic quality as perceived by listeners. This leads to a definition of noise as undesired sound, whilst physically both noise and sound are similar acoustic waves, carried on oscillating particles in the air. Sound is detected by the ear in a mechanical process, which converts the sound waves to vibrations within the ear.

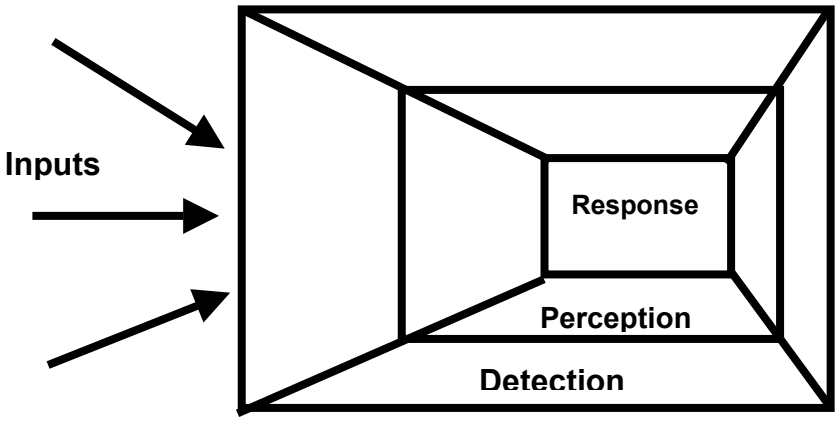

Figure 1. The response chain.

Figure 1 is a simplified diagram of the process, which leads to perception and response. Electrical signals, stimulated by the vibrations in the ear, are transmitted to the brain, in which perception occurs and the sensation of sound is developed. Response is the reaction to perception and is very variable between people, depending on many personal and situational factors, conditioned by both previous experiences and current expectations.

2.2 **Frequency and wavelength.** The frequency of a sound is the number of oscillations which occur per second (Hz), denoted, for example, as 100Hz. Sound travels in air at about 340ms^{-1}, but this velocity varies slightly with temperature. Figure 2 represents sound waves generated by the oscillating strip at the left. As the strip oscillates, it alternately compresses the air, shown by light bands and expands the air, shown by dark bands.

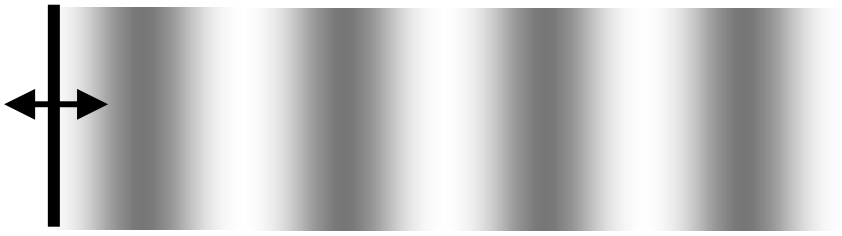

Figure 2. Sound waves.

Since each compression travels at about 340ms^{-1}, after one second the first compression is 340m away from the source. If the frequency of oscillation is, say 10Hz, then there will be 10 compressions in the distance of 340m, which has been travelled in one second, or 34m between each compression. This distance is called the wavelength of the sound, leading to the relation:

velocity = wavelength x frequency, written in symbols as

$$c = \lambda f$$

where c is the velocity of sound, λ the wavelength and f the frequency. The equation gives the relation between frequency and wavelength as in Table 1.

Frequency Hz	1	10	25	50	100	150	200
Wavelength m	340	34	13.6	6.8	3.4	2.27	1.7

Table 1. Frequency and wavelengths of low frequency sound.

In the frequency region 25Hz to 150Hz, wavelengths are of similar size to room dimensions, which can lead to resonances in rooms, discussed in later sections.

2.3 **Noise character and quality.** Pleasant sounds convey pleasant associations. For example, music and birdsong, although early morning seagulls may be considered as noise, because they are an unwanted sound. Here, "unwantedness" is determined by the cognitive environment in which each sound is detected, Character and quality of a noise, combined with our expectations and situation, are important contributors to our response and are considered later.

2.4 **Low frequency noise and infrasound.** The frequency range of infrasound is normally taken to be below 20Hz and that of audible noise from 20Hz to 20,000Hz. However, frequencies below 20Hz are audible, illustrating that there is some lack of clarity in the interpretations of infrasonic and audible noise. Although audibility remains below 20Hz, tonality is lost below 16-18Hz, thus losing a key element of perception. Low frequency noise spans the infrasonic and audible ranges and may be considered as the range from about 10Hz to 200Hz. The boundaries are not fixed, but the range from about 10Hz to 100Hz is of most interest. In later chapters we will not separate infrasound and low frequency noise, but consider the range from 10Hz to 200Hz as continuous.

2.5 **Sources.** Low frequency noise and infrasound are produced by machinery, both rotational and reciprocating, all forms of transport and turbulence. For example, typical sources might be, pumps, compressors, diesel engines, aircraft, shipping, combustion, air turbulence, wind and fans. Structure borne noise, originating in vibration, is also of low frequency, as is neighbour noise heard through a wall, since the wall blocks higher frequencies more than it blocks lower frequencies (Hood and Leventhall, 1971; Leventhall, 1988).

2.6 **Infrasound.** There are a number of misconceptions about infrasound, such as that infrasound is not audible. As will be shown later, frequencies down to a few hertz are audible at high enough levels. Sometimes, although infrasound is audible, it is not recognised as a sound and there is uncertainty over the detection mechanism. Very low frequency infrasound, from one cycle in, say 1000 seconds (0.001Hz) to several cycles a second are produced by meteorological and similar effects and, having been present during all of our evolution, are not a hazard to us. Much of what has been written about infrasound in the press and in popular books is grossly misleading and should be discounted.

2.6.1 **Propagation.** The attenuation of sound in air increases with the square of the frequency of the sound and is very low at low frequencies. Other attenuating factors, such as absorption by the ground and shielding by barriers, are also low at low frequencies. The net result is that the very low frequencies of infrasound are not attenuated during propagation as much as higher frequencies, although the reduction in intensity due to spreading out from the source still applies. This is a reduction of 6dB for each doubling of distance. Wind and temperature also affect the propagation of sound.

2.6.2 **Control.** Infrasound is difficult to stop or absorb. Attenuation by an enclosure requires extremely heavy walls, whilst absorption requires a thickness of absorbing material up to about a quarter wavelength thick, which could be several metres.

2.6.3 **Resonance.** Resonance occurs in enclosed, or partially open, spaces. When the wavelength of a sound is twice the longest dimensions of a room, the condition for lowest frequency resonance occurs. From $c = \lambda f$, if a room is 5m long, the lowest resonance is at 34Hz, which is above the infrasonic range. However, a room with an open door or window can act as a Helmholtz resonator. This is the effect which is similar to that obtained when blowing across the top of an empty bottle. The resonance frequency is lower for greater volumes, with the result that Helmholtz resonances in the range of about 5Hz to 10Hz are possible in rooms with a suitable door, window or ventilation opening.

2.7 **Low frequency noise.** The range from about 10Hz to 200Hz covers low frequency noise. For comparison, the lowest C note on a full range piano is at about 32Hz whilst middle C is at about 261Hz. All the low frequency noise range is audible, although high levels are required to exceed the hearing thresholds at the lower frequencies.

2.7.1 **Propagation.** Similar factors influence the propagation of low frequency noise to those which influence infrasound. However, because of the higher frequencies, air and other attenuations are greater for low frequency noise than for infrasound and more is known about them. Typical air attenuations at 20^0C and 70% relative humidity are:

63Hz	-	0.1dB/km
125Hz	-	0.35dB/km
250Hz	-	1.1dB/km

which shows very low attenuation at 63Hz.

In addition to these there is reduction of 6dB per doubling of distance due to spreading out of the wave and any reduction which might occur due to absorption over the ground or by shielding. It is seen that air attenuations are a small contributor to losses at low frequencies but, since attenuation increase rapidly as frequency rises, air attenuation can be a main contributor at much higher frequencies in the kilohertz range. As a result, noise which has travelled over long distances is normally biased towards the low frequencies.

2.7.2 Control. Low frequency noise and infrasound are steps along the same physical process of wave propagation, so that similar considerations apply to their control, although the shorter wavelengths of low frequency noise make control easier. Thus, a massive single partition, or a complex multiple partition, is needed to stop low frequency noise, with results which improve as the frequency increases. But most walls in buildings are deficient in the low frequency region, so that noise transmission between rooms, and from outside to inside, is a problem. Absorption of low frequency noise requires thick material, such that most sound absorbing linings, typically a few centimetre thick, are ineffective at the low frequencies.

2.7.3 Resonance effects. Resonances in a normal sized domestic room occur in the low frequency region. For example, a room of dimensions 4m by 5m by 2.5m has low frequency resonances from 34 Hz upwards. Resonances increase the sound level in parts of the room whilst decreasing it in others.

Figure 3 illustrates the standing wave of a lowest room resonance, in which the room dimension is one half wavelength of the sound. The level is highest at the end walls and lowest in the centre of the room. It is often possible to detect the differences in level, at different room locations, within a room which has been driven into resonance by low frequency noise.

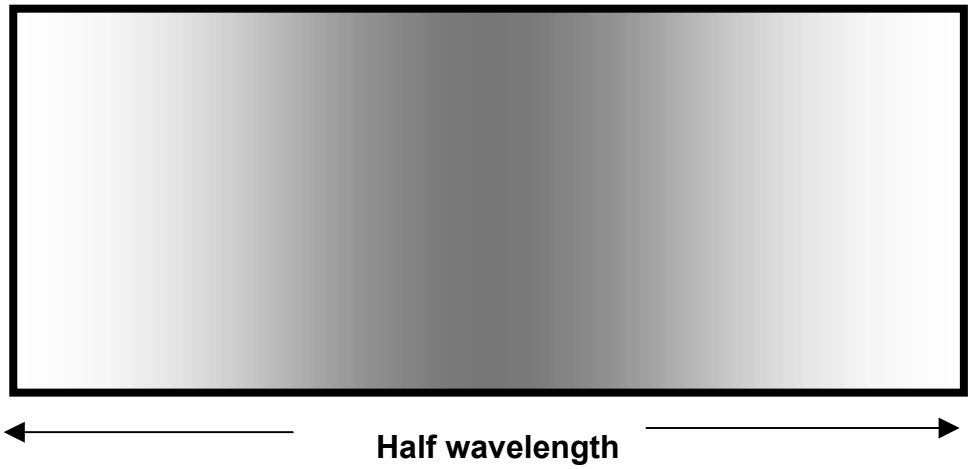

Figure 3. Lowest room resonance.

3. Decibels and measurements

3.1 Noise Levels – the 'decibel'

3.1.1 **Definition:** The decibel is the logarithm of the ratio between two values of some characteristic quantity such as power, pressure or intensity, with a multiplying constant to give convenient numerical factors. Logarithms are useful for compressing a wide range of quantities into a smaller range. For example:

$\log_{10}10 = 1$

$\log_{10}100 = 2$

$\log_{10}1000 = 3$

and the ratio of 1000:10 is compressed into a ratio of 3:1.

This approach is advantageous for handling sound levels, where the ratio of the highest to the lowest sound which we are likely to encounter can be as high as 1,000,000:1. A useful development, many years ago, was to take the ratios with respect to the quietest sound we can hear. This is the threshold of hearing at about 1000Hz, which is taken as 20μPa ($2x10^{-5}$Pa) of pressure for the average person. When the word “level” is added to the word that describes a physical quantity, decibels are implied. Thus, "sound level" is a decibel quantity. When the sound pressure is doubled, the sound pressure level increases by 6dB.

3.2 Measurements

3.2.1 **Weighting networks.** The majority of noise measurements are made using sound level meters (IEC:60651, 2001), which give numerical levels as a representation of the noise. For environmental noise it is normal to use the sound level meter A-weighting, which gradually reduces the significance of frequencies below 1000Hz, until at 10Hz the attenuation is 70dB. The C-weighting is flat to within 1dB down to about 50Hz and then drops by 3dB at 31.5Hz and 14dB at 10Hz. Figure 4 shows the A and C weighting curves.

The G weighting, (ISO7196, 1995), specifically designed for infrasound, falls off rapidly above 20Hz, whilst below 20Hz it follows assumed hearing contours with a slope of 12dB per octave down to 2Hz. This slope is intended to give a subjective assessment to noise in the infrasonic range. A G-weighted level of 95 - 100dBG is close to the perception level. G-weighted levels below 85-90dBG are not normally significant for human perception. However, too much reliance on the G-weighting, which is of limited application, may divert attention from problems at higher frequencies, say, in the 30Hz to 80Hz range.

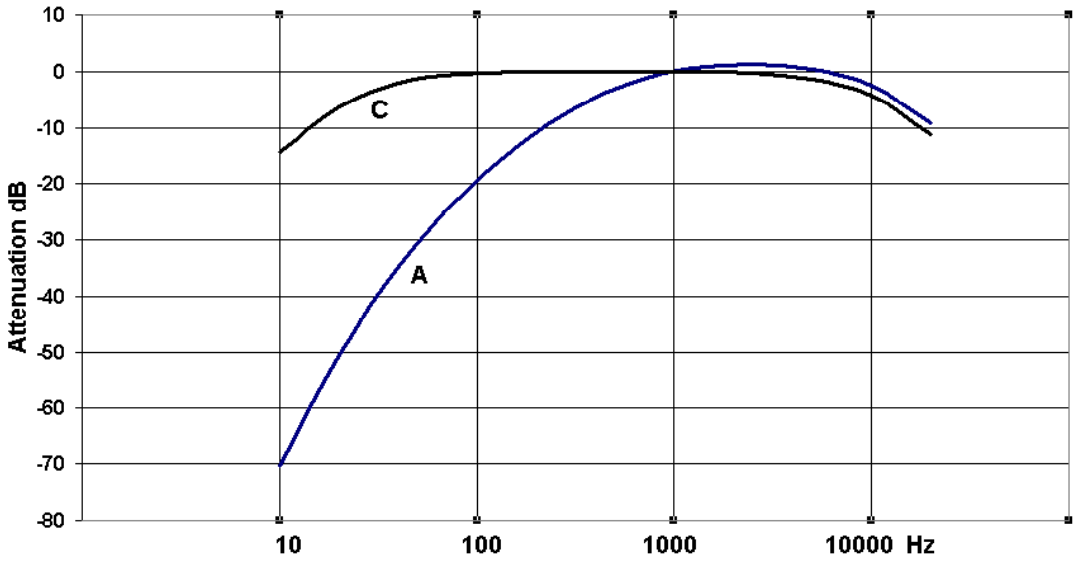

Figure 4. Sound level meter weighting curves – A and C.

Figure 5 shows the G-weighting curve. There is a Linear Weighting, also known as Z-weighting, which has a flat frequency response from 10Hz to 20kHz. More detail of the noise, in particular the presence of tones, can be found from a third octave or narrow band analysis.

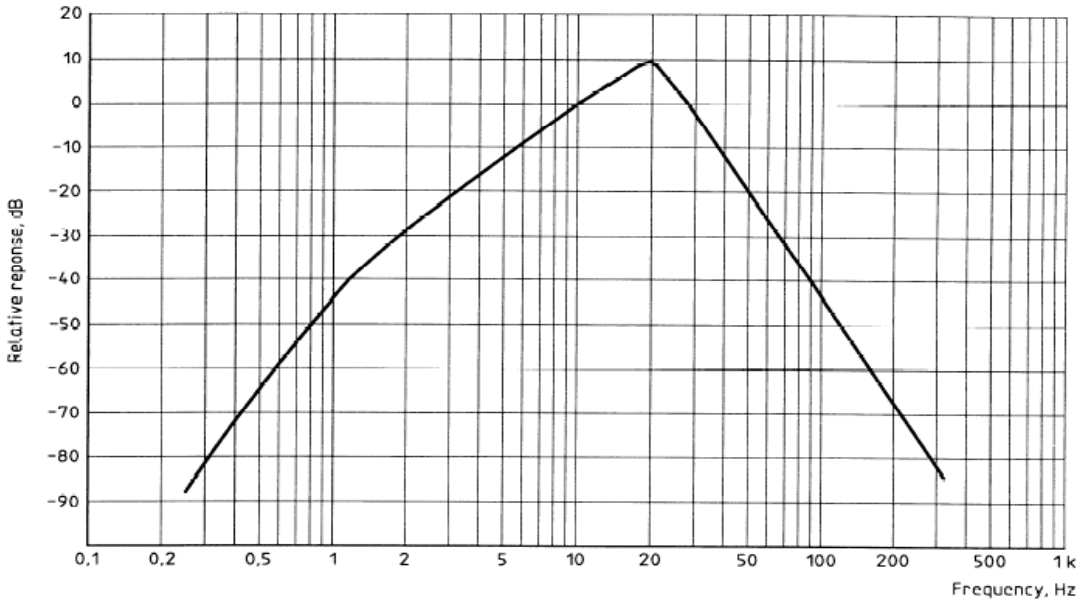

Figure 5. G-weighting for infrasound.

3.2.2 Averaging. Sound level meters give a numerical representation of the noise. However, this is obtained by averaging over a period of time that, for fluctuating noises, is generally longer than the period of the fluctuations, leading to a loss of information on the fluctuations. The widespread use of the equivalent level discards important information on the quality of the noise, its spectral properties and corresponding perceived sound character.

4. The low frequency hearing threshold and loudness

4.1 **Average thresholds.** The aim of studies on the low frequency threshold has been to determine the lowest levels which are audible to an average person, often a young person, with normal hearing. Thus, the threshold is a "quasi-objective" measurement in the sense that it is free from emotional responses. Threshold studies have been carried out on relatively small groups, typically about 10 to 20 subjects, so that differences between experimenters are to be expected. However, the different studies follow the same trend, and the threshold region at low frequencies is now well established. For example, (Corso, 1958; Lydolf and Møller, 1997a; Lydolf and Møller, 1997b; Moller and Andresen, 1984; Møller and Andresen, 1984; Watanabe and Møller, 1990a; Watanabe and Møller, 1990b; Whittle et al., 1972; Yeowart, 1976; Yeowart and Evans, 1974) have all carried out careful studies and give references to earlier work. The frequency ranges covered and method of exposure are as follows.

Corso	5Hz to 200Hz	Monaural headphone
Whittle et al	3.15Hz to 50Hz	Pressure chamber
Yeowart and Evans	1.5Hz to 100Hz	Monaural headphone
	5Hz to 100Hz	Binaural headphone
	2Hz to 20Hz	Pressure chamber
Møller and Andresen	2Hz to 50Hz	Pressure chamber
Watanabe and Møller (a)	25Hz to 1kHz	Free Field
Watanabe and Møller (b)	4Hz to 125Hz	Pressure chamber
Lydolf and Møller	20Hz to 1kHz	Pressure chamber/free field

(Yeowart 1976 is a review of work up to that date)

The different measurement methods – monaural/binaural headphones, pressure chamber, free field – potentially produce different results. For example, binaural listening is 3dB more sensitive than monaural listening - the "binaural advantage". An individual's sensitivity and measured hearing threshold will also be influenced by the method of presentation of the sounds.

Free field levels are often taken in the absence of the subject, whilst pressure chamber measurements are taken in the presence of the subject. However Watanabe and Møller (1990b) found no significant difference between their two measurements in the frequency range of overlap.

Thresholds above 20Hz are standardised by ISO for otologically normal persons within the age range from 18 to 30 years inclusive (ISO226, 1987). Early studies of the low frequency threshold showed discrepancies between

low frequency measurements and ISO 226 at frequencies above 20Hz, where the measurements overlapped. Later measurements have partially resolved these, showing that where the measurements are made in the same laboratory, there is closer agreement in the overlap region between very low frequency pressure chamber measurements and the free field measurements above 20Hz (Lydolf and Møller, 1997a; Watanabe and Møller, 1990b). However, ISO 226 is itself under review and the threshold has been standardised separately for audiometric equipment (ISO 398 - 7, 1996). A German Standard for environmental low frequency noise (DIN:4560, 1997) circumvents the difference by extrapolating the threshold of ISO 226 from 20Hz, the lowest standardised frequency, by 8dB rise per third octave down to 8Hz. This gives thresholds which are lower than most measured ones in the infrasonic region.

4.1.1 Current threshold values. The thresholds found by Watanabe and Møller (1990b) are shown in Figure 6, which also includes the limit of 85dBG up to 20Hz and 20dBA in the range 10-160Hz. The threshold measurements from 20Hz to 125Hz are very close to the ISO 389-7 threshold (ISO389-7, 1996). Figure 6 gives the threshold at 4Hz as about 107dB, at 10Hz it is 97dB, at 20Hz it is 79dB and at 50Hz it is 46dB. Note that, at about 15Hz, there is a change in threshold slope from approximately 20dB/octave at higher frequencies to 12dB/octave at lower frequencies. This is a consistent finding by different experimenters, occurring within the range 15Hz to 20Hz, depending on which frequencies have been used in the measurements. It has not been fully explained, but is thought to be due to a change in the aural detection process, occurring in the frequency region at which tonality of the auditory sensation is lost.

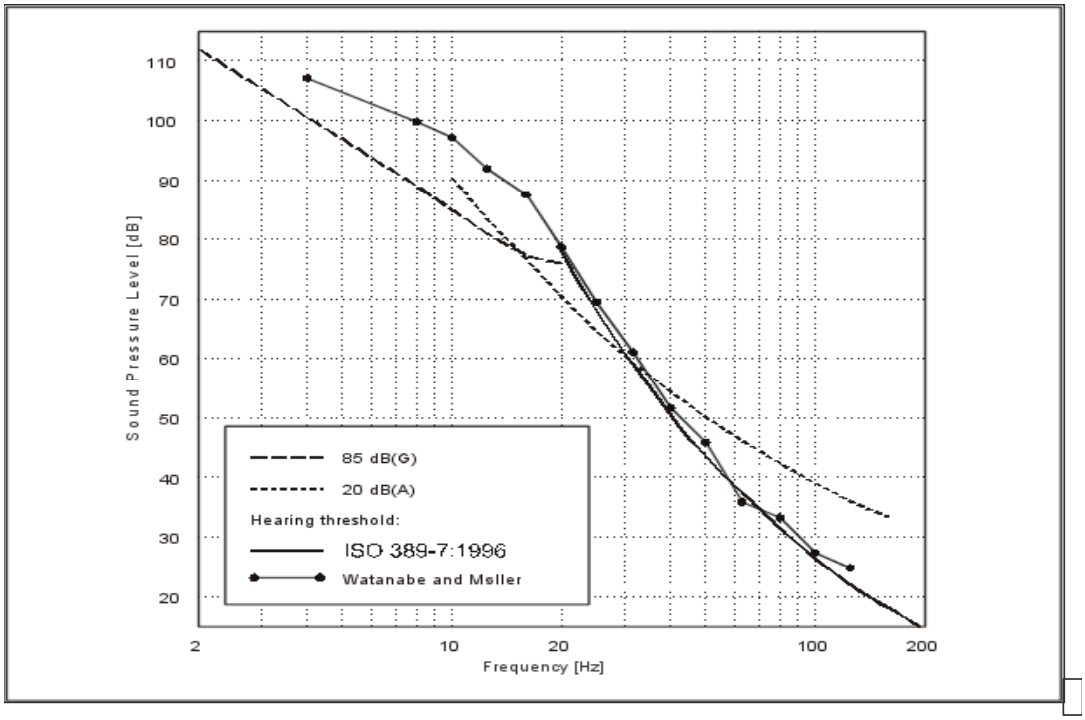

Figure 6. Threshold levels after Watanabe and Møller (1990b).

The 50% and 10% hearing thresholds for an otologically unselected 50 – 60 year old age group has been compared with that for otologically selected young adults. (van den Berg and Passchier-Vermeer, 1999a). The older population is typically 6 – 7dB less sensitive than the younger one, whilst the hearing sensitivity which is exceeded by 10% of the population is, typically, 10-12dB below the average, 50% level. It was also estimated that the 5% hearing level was 2dB below the 10% hearing level.

4.2 **Individual thresholds.** The threshold levels described above are averaged over groups of subjects. The threshold of an individual may differ from the average. Investigations at higher frequencies have shown that an individual threshold exhibits a “microstructure” in which there are fluctuations in sensitivity of up to 12dB at specific tones. (Cohen, 1982).

Further investigations of this effect were made at both low and high frequencies (Benton, 1984; Frost, 1980; Frost, 1987). For example, Frost (1987) measured thresholds at 5Hz intervals over the range 20Hz to 120Hz with results such as in Figure 7, which compares two subjects, one of whom is about 15dB more sensitive than the other at 40Hz. Both subjects had similar audiograms at 250, 500 and 1000Hz.

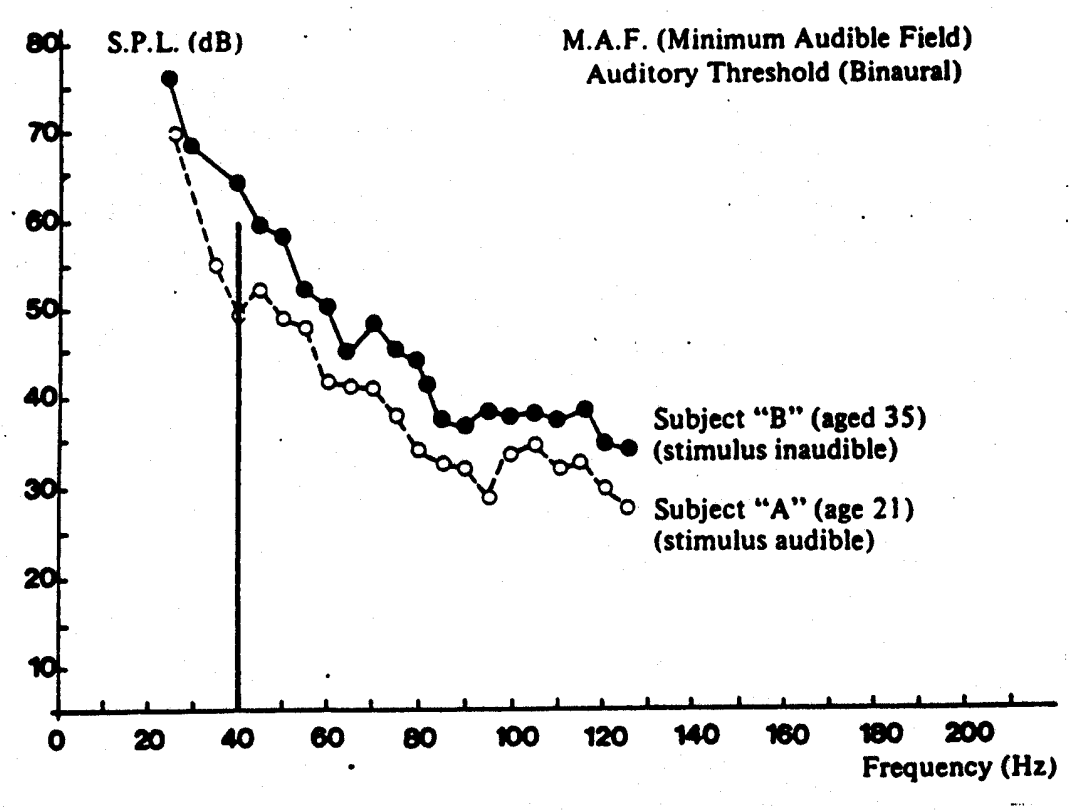

Figure 7. Individual thresholds showing regions of enhanced sensitivity.

Yamada and colleagues (Yamada, 1980) reported male and female thresholds separately, measured in a pressure chamber at third octave frequencies from 8Hz to 63Hz. For his subjects, women were about 3dB more sensitive than men except at the lowest two frequencies, 8Hz and 10Hz. It was also found that individual differences are large, one male subject having a threshold which was 15dB more sensitive than the average.

It is clear that the audiogram is not a smooth curve and that there are pronounced individual differences. Low frequency audiograms of complainants have shown that some hum complainants have low frequency hearing which is more sensitive than the average threshold, whilst others are less sensitive (Walford, 1978; Walford, 1983), as would be expected in any population of subjects. Thus, complainants do not necessarily have enhanced hearing acuity at low frequencies.

4.3 **Loudness at low frequencies.** Loudness is also a “quasi-objective” measurement, although, as with the threshold, its determination depends on the subject’s responses. Loudness is measured against the loudness of a tone at 1000Hz. Experimentally, the subject adjusts the level of the sound under investigation until it sounds equally loud to the 1000Hz reference tone. This is the way in which the equal loudness contours of ISO 226:1987, shown in Figure 8 were developed. It is also possible to use an intermediate frequency, F2, first comparing F2 with the 1000Hz reference and then the test tone, F3, with F2, in order to compare F3 with 1000Hz. For example, 50Hz might be compared directly with 1000Hz, but lower frequencies compared directly with 50Hz and indirectly with 1000Hz. The unit of loudness is the "phon", which is the level of a 1000Hz tone that has the same loudness as the test tone when the tones are presented as plane waves, with the subject facing the direction of the waves.

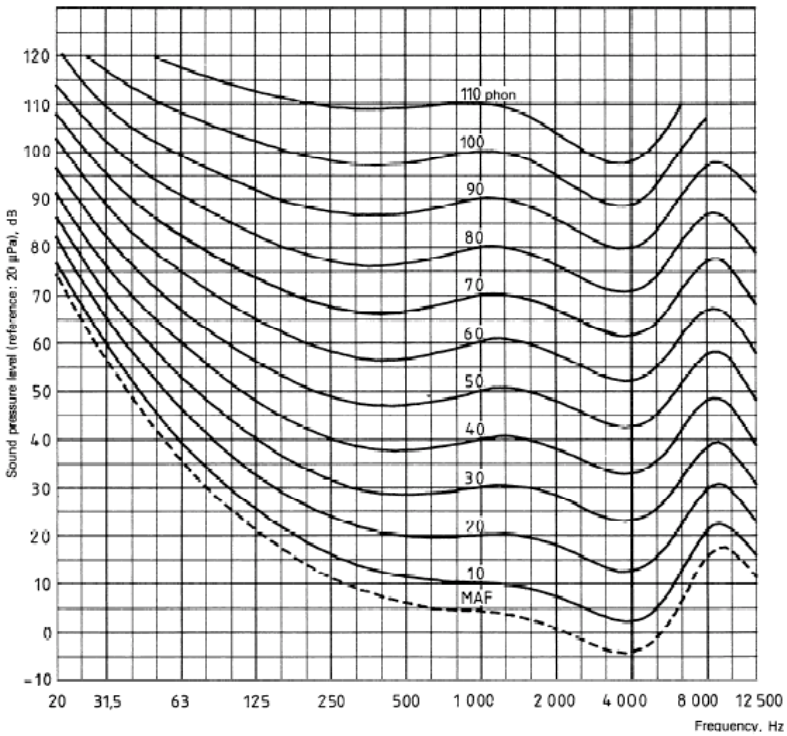

Figure 8. Equal loudness contours (ISO 226).

Some threshold investigations at low frequencies have also included measurement of equal loudness contours (Lydolf and Møller, 1997a; Watanabe and Møller, 1990a; Whittle et al., 1972; Yeowart, 1976). Figure 8 , showing the equal loudness contours above 20Hz, illustrates the trend that, as the frequency reduces, the contours come closer together. Thus, in Figure 8, the 80 phon range of loudness at 1000Hz, from 10dB to 90dB, spanning 80dB, is compressed into 40dB at 20Hz. The mid-frequency rule of thumb that a 10dB increase in level represents a doubling of loudness, fails at low frequencies. At 20Hz a doubling of loudness occurs for a level change about 5dB, and requires a smaller change at lower frequencies.

The main loudness level measurements at very low frequencies have been by (Moller and Andresen, 1984; Møller and Andresen, 1984; Whittle et al., 1972). Figure 9, from Møller and Andresen, compares the results. Møller and Andresen made measurements at octave frequencies from 2Hz up to 63Hz. Whittle's measurement frequencies were at octaves between 3.15Hz and 25Hz, followed by third octave frequencies to 50Hz. There is good agreement over the main range with the continuing tendency for the contours to become closer as the frequency reduces. The more rapid growth in loudness at low frequencies is an important factor in its subjective effects.

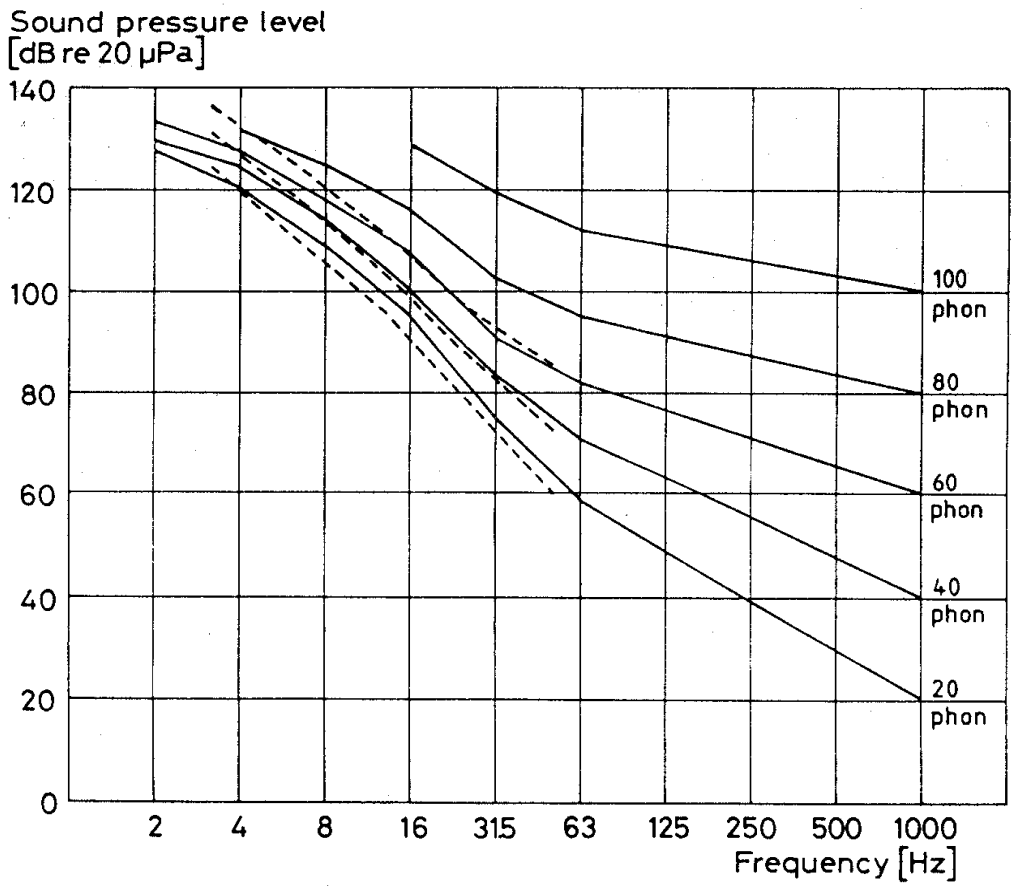

Figure 9. Loudness measurements.

——— **Møller and Andresen**
- - - - - - - **Whittle**

5. False Perceptions

There is always low frequency noise present in an ambient "quiet" background. Origins are often from transportation or industrial sources, which are too far away to be clearly identified. However, depending on the type of location, typical levels might rise rapidly below 50Hz and reach 40-50dB at frequencies below 20Hz. An investigator may conclude that this rise in low frequency levels is the source of the complaint, neglecting that the threshold at 20Hz is higher than 70dB. As a general rule, broadband noise which is more than 20dB below the average threshold is unlikely to be a problem, as it lies below the threshold of the most sensitive persons.

The instances when a noise is heard by a complainant, but cannot be measured or detected by instruments at significant levels, make it necessary to consider the possibility that a mechanism other than an airborne sound is responsible, leading to a false perception of noise. Potential origins of false perceptions include tinnitus, electromagnetic waves, synaesthesia, hypnagogic effects and the "cognitive itch".

5.1 **Tinnitus.** Tinnitus has often been used as the "fall back" explanation, when it has not been possible to measure a noise. In addition to tinnitus arising in the hearing mechanism, there are low frequency fluctuations within the body, mainly associated with blood flow, which are known to produce audible effects. In an investigation which included both hum sufferers and tinnitus sufferers, Walford (1983) attempted to separate the responses of the two groups. Both experimental groups were asked to match the frequencies of their sensations, in both level and rate of throb. This was done by adjusting the frequency, throb rate and amplitude of an oscillator. There was overlap between the two groups, with matched frequencies ranging from 15Hz to 196Hz and throb rates from zero to over 5 per second. There was a clustering of frequencies around 40Hz with throb rates of 1 – 2 per second. The overlap in sensations emphasises the difficulties of separating tinnitus patients from those who hear an external noise. Walford attempted the separation by an earmuff test. First the effectiveness of the earmuffs was tested against a matched tone from an oscillator, in order to demonstrate their attenuation at that frequency. If the earmuffs, in the presence of the problem noise, then do not reduce this noise, it is likely to be tinnitus. If they are effective against the noise, there is likely to be an external source.

An important element of this work was when the low frequency noise sensitives were matching, from memory, the levels at which they hear the noise in their homes. The matching sounds were all above average threshold levels, in many cases by 20dB to 40dB. This means that these sounds would have been audible to most listeners, although they were not heard by investigators and others. Several points come from this:

If the matching levels were correct, the effects were likely to be tinnitus.

The subjects may have a very imperfect memory of the sounds they hear in their homes.

The subjects were matching how they felt about the noise, rather than what they heard, determined by long-term antagonistic conditioning.

5.2 **Electromagnetic waves.** It has been known for some time that electromagnetic waves may produce auditory sensations in persons close to a transmitter although, as shown by calculations later in this section, in most practical exposures the levels of electromagnetic radiation are considerably below those where auditory sensations have been observed.

5.2.1 **Review.** An early paper (Frey, 1962) showed that good high frequency hearing in the listener was necessary for perception. Frey also listed other effects, depending on the transmitter parameters. These effects included buffeting of the head, dizziness or nausea and pins-and-needles sensations. However, his main work was on hearing sensations produced by pulsed waves in the range 425MHz to 3000MHz. He found that a peak electrical field strength of around 15V/cm (1500V/m) was the threshold value for perception when using pulse duty cycles of around 0.001 to 0.01. Very low duty cycles (0.0004) required higher peak fields. The work was carried out in a laboratory area of 70-90dB acoustic background noise and Frey considered that thresholds would be lower in quieter surroundings.

A recent review gives a clear survey of existing material (Elder and Chou, 2003 (submitted for publication)) and also available under the title of the paper on grouper.ieee.org/groups/scc28/sc4/.

Auditory perception, which follows from a rapid transient heating of about 10^{-6} ^{0}C, depends on the energy in a single pulse and not on the average power density, typical sensations being click, buzz, hiss, knock or chirp. The effective stimulation range is 200MHz to 10,000MHz and the ability to hear the effects of radio frequencies in this range depends on good high frequency acoustic hearing, in the kilohertz range. Conversion starts outside the cochlea, by absorption of RF energy in tissues in the head, leading to rapid thermal expansion. The resulting pulse feeds by bone conduction to the cochlea, which is very sensitive. (Note that the displacement of the eardrum at the level of ordinary conversation is about 10^{-10} m, which is sufficient to stimulate the cochlea to sense a sound of moderate level (Stephens and Bate, 1966)).

Elder and Chou give examples of values of RF stimulation to produce distinct clicks such as:

Frequency, 3000MHz: 5μs pulse widths: repetition rate $0.5s^{-1}$: peak power density $2.5W/cm^2$.

In experiments on exposure of humans to radar waves, the RF induced sounds disappeared when an aluminium fly screen was placed between the subject and the radar. It was also found that a small metal screen, about 50mm x 50mm, placed over the temporal lobe of the brain, completely stopped the sound. Additional information and international standards are given in a survey of effects of radio wave exposure (Firstenberg, 2001).

5.2.2 EM waves and sensitivity to LF noise. The audible sensations produced by electromagnetic waves do not closely match the sounds reported by low frequency noise sensitives. As good high frequency hearing is required, the older complainants may not be able to perceive the sounds. However, the buffeting of the head, dizziness or nausea and pins-and needles sensations noted by Frey do match some complainants. These effects do not appear to have been followed up and are not referred to in the comprehensive review by Elder and Chou. It is possible that the effects will manifest only at very high exposure levels, which requires a subject to be close to a transmitter.

It is necessary to relate the electromagnetic levels used in the hearing experiments with those to which people are normally exposed. Simple predictions can be made of energy density and field strength at distances from a transmitter. For example, www.mitedu.freeserve.co.uk/Theory/antenna.htm gives the power density (power received per unit area) at a distance *d* from a transmitter of power P_t as

$$P_r = \frac{P_t}{4\pi d^2} \text{ W/m}^2$$

The field strength is

$$E = \frac{\sqrt{30P_t}}{d} \text{ volts/m}$$

Then, say, at a distance of 10m from a transmitter of power 100W,

$$\text{Pr} = 0.08 \text{ W/m}^2 = 8\text{x}10^{-6} \text{ W/cm}^2$$

$$\text{E} = 5.5 \text{ V/m} \quad = 0.055 \text{ V/cm}$$

These values are considerably below the levels of 15V/cm and 2.5W/cm^2 quoted above as typical levels for an effect.

Pulsed radars generate very high peak powers, say, 1MW. (WHO, 1999) The radiation is very directional and falls off rapidly at the side of the main beam. For a 1MW peak power, at a distance of 100m, the formula for P_r above gives P_r = 8W/m^2. However, this must be multiplied to allow for the directionality of the aerial, which might typically lead to a power gain on the axis of the main beam of 30dB (1000 times), resulting in 8000W/m^2, or 0.8W/cm^2. This is lower than the levels given by Elder and Chou for the auditory effect. Additionally, it is unlikely that people will be exposed to the main beam. The experimental work on audibility of RF pulses has been carried out with subjects close to the RF sources and consequently exposed to higher levels than would be received by the public at normal source distances.

5.2.3 Growth of EM waves. The growth of EM waves is one of the major environmental changes over the past 100 years, particularly in the last 50 years. Frequencies have been extended at both low and high ends of the spectrum. For example, Extremely Low Frequencies (ELF) start at about 3Hz and extend to a few kilohertz, such that electromagnetic frequencies overlap with audio frequencies. ELF is used for communication with submerged submarines, since the low frequencies penetrate deep into water. The transmission frequency is 76Hz, modulated between 72Hz and 80Hz. It is not known whether work has been carried out to detect auditory effects from ELF. Coincidentally, the transmission commenced in the 1960's, which is a start time for growth in complaints of low frequency noise, but absorption of energy by body tissues is very low at low frequencies.

5.2.4 Power lines. Much work has been carried out on biological effects of power lines which, at 50Hz or 60Hz, are similar frequency to the ELF transmissions. A detailed explanation of the effects of power line radiations does not mention auditory effects.(National Institute of Environmental Health Sciences and National Institute of Health (Australia), 2002). This may be because the audible sensations produced by electromagnetic waves depend on fluctuation in the stimulus wave, typically as short pulses. Steady waves from power lines, if they have an effect, will produce a steady change in the head, which will not result in audible signals. A requirement for auditory sensations induced by the thermal effect is that the transient electromagnetic energy is absorbed in the tissues of the head. This is a frequency dependent effect, occurring mostly between about 200MHz and 10,000MHz (Elder and Chou 2003). Absorption is very low at ELF.

5.2.5 Conclusions. A conclusion is that, although auditory signals are produced by pulsed electromagnetic waves, there is, as yet, no evidence to show that the effects are similar to those experienced by people who are sensitive to low frequency noise. There is a gap in knowledge, which might be clarified if the non-auditory effects referred to by Frey (1962), can be replicated at typical environmental exposure levels of electromagnetic waves. However, the weight of evidence is against EM waves being a source of the types of effects experienced by low frequency noise complainants.

5.3 Synaesthesia. Synaesthesia is a "cross talk" effect in the brain in which one sensory pathway links across to another, resulting in two outputs from one input. ((Baron-Cohen and Harrison, 1997; Grossenbacher, 1997; Rich and Mattingley, 2002). This is indicated in Figure.10. The auditory input leads to both auditory and visual perceptions. Another model requires feedback from a multimodal nexus which receives inputs from multiple sense modalities, thus acting as a link between them.

The question to be addressed is: In the cases where complaints persist, but noise cannot be measured, could the complainants have a form of synaesthesia in which a sensory input of another modality leads to an auditory percept?

The commonest form of synaesthesia is the linking of colours to printed letters and numbers. The letters may appear to be coloured even though they are printed as black. Other effects are to "see" music in colours. It is estimated that about 1 in 2500 people are synaesthetes, of whom more are women than men and a high proportion are left-handed.

5.3.1 **Auditory effects.** Associate Professor Sean Day of Miami University, also President of the American Synaesthesia Association, gives statistics based on a sample size of 572, some of whom have more than one type of synaesthesia. See Sean Day's personal web page www.users.muohio.edu/daysa/types.htm. The commonest occurrence is black printed letters appearing as coloured (68.8%), but there is a small number, about 1%, who hear sound when the stimulus is from smell, taste or touch.

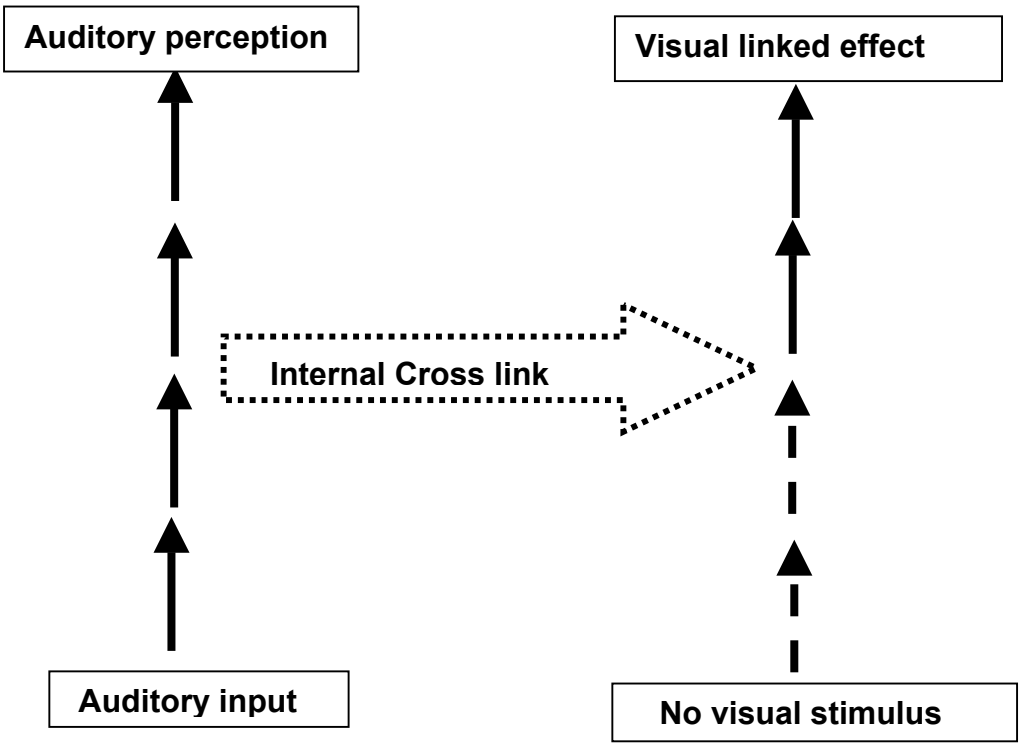

Figure 10. Illustrating synaesthesia, a sound causing a visual effect.

Baron-Cohen (Baron-Cohen, 1996) describes a synaesthete who links colours to sounds and also has the reverse experience, hearing sounds when seeing colours. The effect is described as leading to "massive interference, stress, dizziness, a feeling of information overload and a need to avoid those situations which are either too noisy or too colourful".

It is difficult to assert that synaesthesia is an explanation of some of the unsolvable low frequency noise problems. Synaesthesia is often a lifelong condition, whilst many low frequency noise complaints have a sudden onset. However, synaesthesia can be acquired through seizures or drug use, neuron degeneration and damage to the brain or spinal cord. Thus, synaesthesia is a candidate explanation where noise cannot be measured, but not a very strong candidate.

5.4 **Reception through the skin.** The skin contains multiple sensors which respond to touch, pressure, temperature, pain etc. The Merkel cell, Meissners corpuscles and Pancinian corpuscles respond to vibration as indicated in Figure 11, reproduced from Jones (Jones, undated). There is the question: are these more or less sensitive receivers than the ear at very low frequencies? The high displacement thresholds shown in Figure 11 indicate that, to a normally hearing person, perception through the ear will take precedence. This is borne out by experiments with normally hearing and profoundly deaf persons (Yamada et al., 1983). The threshold of sensation of the deaf subjects was 40-50dB above the hearing threshold of those with normal hearing up to 63Hz and greater at higher frequencies. For example about 100dB greater at 1kHz, at which level perception was by the subject's residual hearing. Deaf subjects felt sensations mainly in the chest.

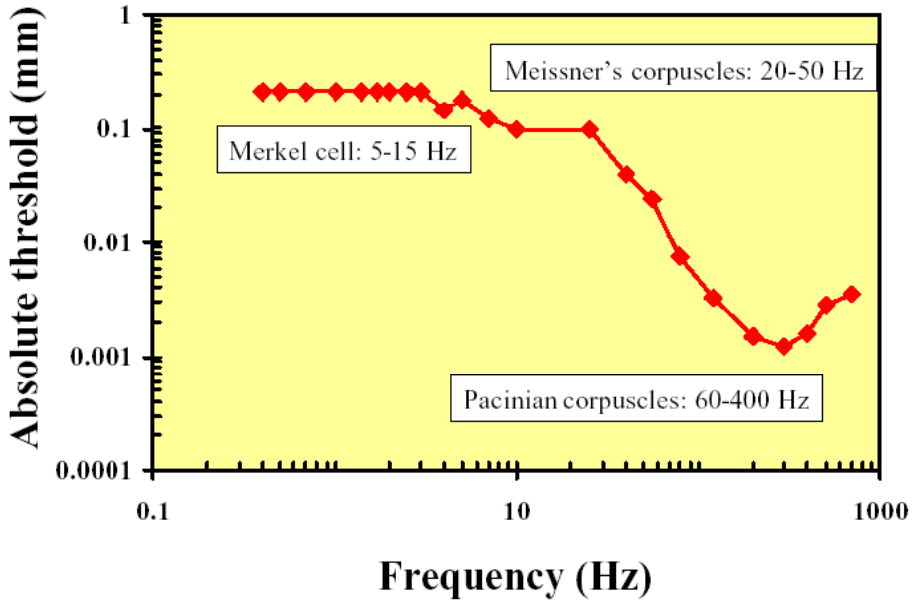

Figure 11. Threshold sensitivity of receptors in the skin.

5.5 **Hypnagogic and hypnopompic experiences.** These terms describe the unusual experiences which might occur when a person is falling asleep (hypnagogic) or waking up (hypnopompic). They are sometimes associated with sleep paralysis, when it is not possible to move, although aware of the surroundings. In addition to immobility, there may also be a sensed presence, pressure on the body, floating sensations, sounds, a visible form and fear. The effects, which are associated with the rapid eye movement (REM) sleep stage, have been investigated amongst a large group of undergraduates (Cheyne et al., 1999). The frequency of occurrences amongst a sample of 870 students is shown in Table 2. About 12% of the sample experience sounds. Cheyne gives a description of the auditory effects on http://watarts.uwaterloo.ca/~acheyne/.

Experience	Frequency	Proportion
Immobility		
Never	616	0.71
Once	70	0.08
2 – 5 times	105	0.13
5 times	75	0.09
Hallucinoid experiences		
Sensed presence	130	0.15
Body pressure	106	0.12
Floating	93	0.11
Sounds	99	0.12
Visible form	75	0.09
Fear	117	0.14

Table 2. Frequencies and proportions of individuals experiencing sleep paralysis and associated hallucinoid experiences. (Cheyne et al 1999).

The auditory effects are described as buzzing, grinding, humming, ringing, roaring, rushing, screeching, squeaking, vibrating, whirring, and whistling. Bodily sensations of tingling, numbness or vibrations sometimes accompany the sounds. There is a parallel between these descriptors and complainants of low frequency noises, especially for those whose experience is worse when trying to sleep.

It is not suggested that hypnagogic effects are the explanation for low frequency noise disturbance, but it is possible that they could explain some of the extreme effects which complainants feel in bed and which are attributed to the complaint noise.

5.6 **The "cognitive itch".** It has been suggested by Sargent (Sargent, 1996) that subjects could become sensitive to a noise, possibly developing an ongoing "memory" of it. We have all experienced certain "catchy" tunes repeating in the head – the "cognitive itch" (Kellaris, 2001). The main characteristics of such tunes are repetition, simplicity and incongruity, all of which hold the attention. In particular, repetition causes an automatic pattern echo in the brain. The "cognitive itch" metaphor arises since, in the same way that one scratches an itch, the cognitive itch demands attention through internal repetition of its sounds. It is related to endomusia, a syndrome in which melodies are recalled in the head, possibly to an obsessive extent .

A similar effect to the cognitive itch may be relevant to some of the low frequency noise problems, in which exposure has developed a memory of the noise.

6. Development of enhanced susceptibility

It is known that different regions of the brain are responsible for different functions. The brain also possesses "plasticity", in the sense that parts within the same region may change their function. (Schnupp and Kacelnick, 2002). For example, extensive training in a frequency discrimination task leads to improved discrimination ability and an expansion of the cortical area responsive to the frequencies used during training. Schnupp and Kacelnick quote supporting work on animals as follows:

> Guinea pigs, trained to associate presentation of a particular pure tone with an unpleasant, but mild, electric shock to the paw, learned to avoid the shock by withdrawing their paw when presented with the tone. Subsequent electro -physiological examination indicated that neurons, originally tuned to frequencies on either side of the conditioning frequency, had shifted their tuning curves towards that frequency. The shift of frequency tuning meant that more cells in the cortex were available to signal the presence of the conditioned stimulus and that this signal is sensed clearly and unambiguously.
>
> Owl monkeys, trained through a reward and denial regime to discriminate a target frequency from different frequencies, were shown to have a shift in neural tuning curves and a sharpening of frequency tuning for the target.

In humans, there is considerable plasticity in the brain during its early development, requiring appropriate stimuli for proper growth. Plastic adaptation is slower in the adult brain. Two examples of plastic adaptation are:

> London taxi drivers have been shown, through magnetic resonance imaging, to have an enlarged posterior hippocampus compared with control subjects who did not drive taxis.(Maguire et al., 2000). Taxi driver's anterior hippocampal regions were, however, smaller than controls. Posterior hippocampal volume correlated positively with time spent as a taxi driver, whilst anterior hippocampal volume correlated negatively. The conclusion is that, in order to learn the thousands of routes required for their work, that part of the brain associated with spatial navigation, the posterior hippocampus, enlarged at the expense of neighbouring regions.
>
> There has been a similar finding for skilled musicians (Pantev et al., 1998). Cortical reorganisation was greater the younger the age at which learning began.

The significance of these findings for low frequency noise sufferers is:

- *There is clear evidence that the brain is able to adapt to stimuli.*
- *If sufferers spend a great deal of time listening to, and listening for, their particular noise, it is possible that they may develop enhanced susceptibility to this noise.*
- *Enhanced susceptibility is therefore a potential factor in low frequency noise problems.*

7. Objective effects

7.1 **Hearing loss.** High levels of A-weighted noise lead to damage to hearing. Do high levels of low frequency noise, whose measured levels would be depressed on an A-weighted measurement, have similar effects? This was one of the early investigations in the American Space Programme (Mohr et al., 1965). Mohr exposed subjects to single tones and narrow bands of noise in the range 10-20Hz, at levels of 150-154dB for two minutes. There was no change in hearing sensitivity as reported by the subjects and no measured temporary threshold shift (TTS) at about one hour after exposure. In other work (Jerger et al., 1966), subjects were exposed for 3 minutes to 7-12Hz at levels 119-144dB. TTS of 20-25dB was found at high frequencies (3kHz to 6kHz), but recovery was complete in a few hours. Nixon (Nixon, 1973) used a piston-phone coupled to the subject's ear via an earmuff to produce levels of 135dB at 18Hz. Six five minute exposures were used with one to two minute rest periods between. TTS was observed in one third of the subjects used, but this recovered after about half an hour. Later work (Burdick et al., 1978) indicated that there may be some permanent threshold shift (PTS) for long term high level exposure. In one experiment, chinchilla were exposed for three days to octave band noise at, 100dB, 110dB and 120dB centred on 63Hz. The highest level led to PTS of up to 40dB at 2kHz in the chinchilla. When human subjects were exposed to the same low frequency noise at 110dB and 120dB for four hours, a TTS of about 15dB resulted, extending from low frequencies up to 2kHz. The frequency used by Burdick et al is higher than in the other experiments and might be expected to have a greater effect. There is an indication that long-term exposure to very high levels may cause permanent hearing loss.

Aural pain is produced by exposure to high levels of noise, occurring when the displacement of the middle ear system exceeds its normal limits. Thresholds of pain are given as rising from about 140dB at 30Hz to 165dB at 2Hz (von Gierke and Nixon, 1976). However, there may be people with middle ear problems whose pain threshold is lower than this.

It appears that low frequency noise will produce TTS in some subjects after short exposure, but that the recovery is rapid and complete. Work has not been carried out on the effects of very long exposures to high levels of low frequency noise. The levels experienced in exposure to environmental low frequency noise are considerably lower than the levels used in the hearing loss experiments described above.

7.2 **Body Vibrations.** It is possible that body organs resonate within the low frequency range. Complainants of low frequency noise sometimes report a feeling of vibrations through their body.

7.2.1 **Whole body exposure.** Work has been carried out on body vibrations produced by whole body exposure to low frequency noise.(Brown, 1976; Kyriakides, 1974; Leventhall et al., 1977; Takahashi et al., 2002; Takahashi and Maeda, 2002). The vibratory response of the body to acoustic stimulation

is different from its response to mechanical vibration through the feet or seat. Low frequency acoustic stimulation acts over the whole body surface. The work by Brown, Kyriakides and Leventhall was carried out in a small chamber, in which it was possible to maintain a constant excitation level of noise over the frequency range from 3Hz to 100Hz at up to 107dB. Resonance was detected by an accelerometer mounted on a small plate on an elastic belt, which held the accelerometer in contact with the body. For chest resonance measurements, the accelerometer was positioned over the sternum. Other measurement sites were at the front of the stomach and on the shin muscles. The output of the accelerometer was recorded during a frequency sweep from 3Hz to 100Hz at 107dB. The most prominent effect was a chest resonance, occurring in the range from about 30Hz to 80Hz, depending on stature and gender, but mostly near the centre region of this range. The vibration was clearly felt by the subjects and modulated their voices, producing a croaky effect. Repeating the measurements with the subjects breathing a helium-oxygen mixture resulted in the same chest resonance frequency, although voices acquired the typical higher pitch of helium speech. This isolates the resonance to a structural source, the rib cage, rather than within body cavities, such as the lungs. A chest resonance is shown in Figure 12 for a male subject and excitation at 107dB. The maximum acceleration is 0.05g. There were smaller effects at other body locations.

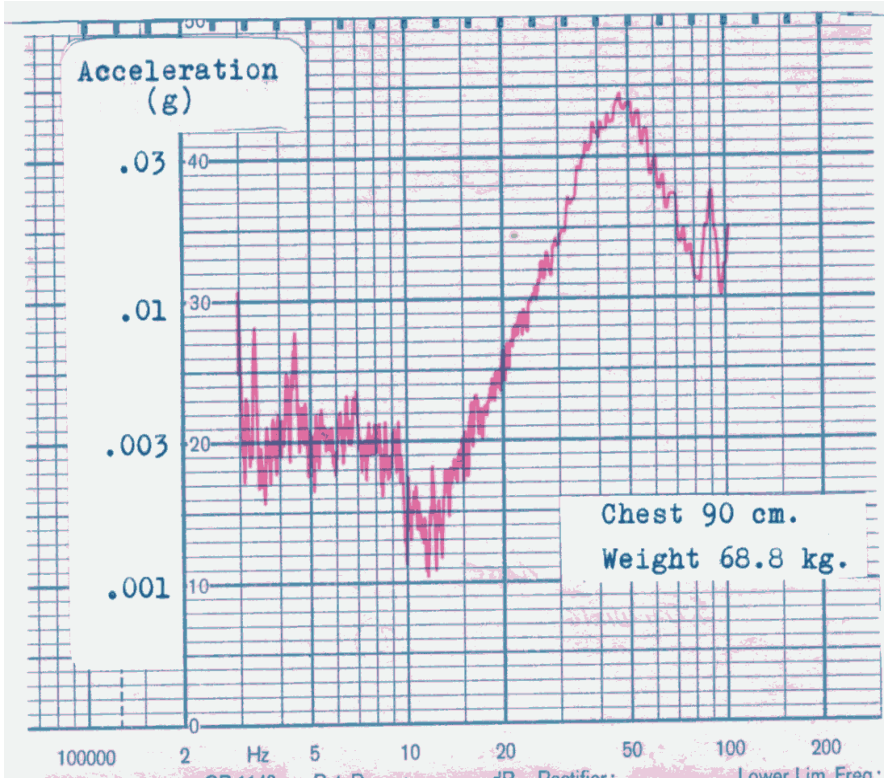

Figure 12. Example of male chest vibration at 107dB

Takahashi and colleagues used a chamber which, because of its size, was limited to a maximum frequency of 50Hz, above which the spatial uniformity of the sound field deteriorated. Measurements were made using single frequencies (20, 25, 31.5, 40 and 50Hz) at levels of 100, 105 and 110dB at the following locations: the forehead, the right and left anterior chest and the right and left anterior abdomen. Further work used white noise and complex noise (combined 31.5Hz and 50Hz) excitation. The general trend was for vibration levels to increase as the frequency increased, but resonance was not shown, due to the limited frequency range of the measurements. The results of the complex tone measurements led to the conclusion that the human body acts as a mechanically linear system in response to airborne excitation.

7.2.2 Conclusions. The work on body vibrations has a limited significance for people in their daily life. Vibrations are sometimes experienced when, as a pedestrian, a bus or lorry passes by, since these vehicles often emit noise at around 60Hz. Body vibrations are a pleasurable effect at discos and rock concerts, as shown by the attendees who cluster near the bass loudspeakers. Typical levels of infrasound and low frequency noise, as experienced in homes, are not high enough to cause significant body vibrations, since, as shown in Figure 12. the resonant gain for the chest vibrations was about 25dB and inherent body vibrations will mask excitations resulting from levels of noise below 70-80dB.

8. Annoyance

8.1 **The meaning of annoyance.** Annoyance has roots in a complex of responses, which are moderated by personal and social characteristics of the listeners. (Belojevic and Jokovljevic, 2001; Benton and Leventhall, 1982; Fields, 1993; Grime, 2000; Guski, 1999; Guski et al., 1999; Kalveram, 2000; Kalveram et al., 1999; Stallen, 1999).

For example, Guski (1999) proposes that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables, which are shown in Table 3. Noise annoyance in the home is considered as a long-term negative evaluation of living conditions, dependent on past disturbances and current attitudes and expectations. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, hate etc, some of which combine to produce the adverse reaction.

Personal Moderators	**Social Moderators**
Sensitivity to noise	Evaluation of the source
Anxiety about the source	Suspicion of source controllers
Personal evaluation of the source	History of noise exposure
Coping capacity with respect to noise	Expectations

Table 3. Noise Annoyance Moderators.

Figure 13, modified from Guski (1999) in order to emphasise the central nature of the personal factors, summarises the interactions**.** The interpretation of Figure 13 is as follows. The noise load causes activity interference (e.g. to communication, recreation, sleep), together with vegetative reactions (e.g. blood pressure changes, defensive reactions). Activity interference develops into annoyance and disturbance. Prolonged vegetative reactions may lead to effects on health. Personal factors feed into the outer boxes of Figure 13, moderating the complainant's complex of responses. The social factors moderate how the complainant interacts with external authorities in attempting to deal with the annoyance. Social factors may also interact with health effects, as some social classes may more readily seek medical assistance. The personal and social moderating factors are so variable that Grime (2000) questions the feasibility of a national noise policy.

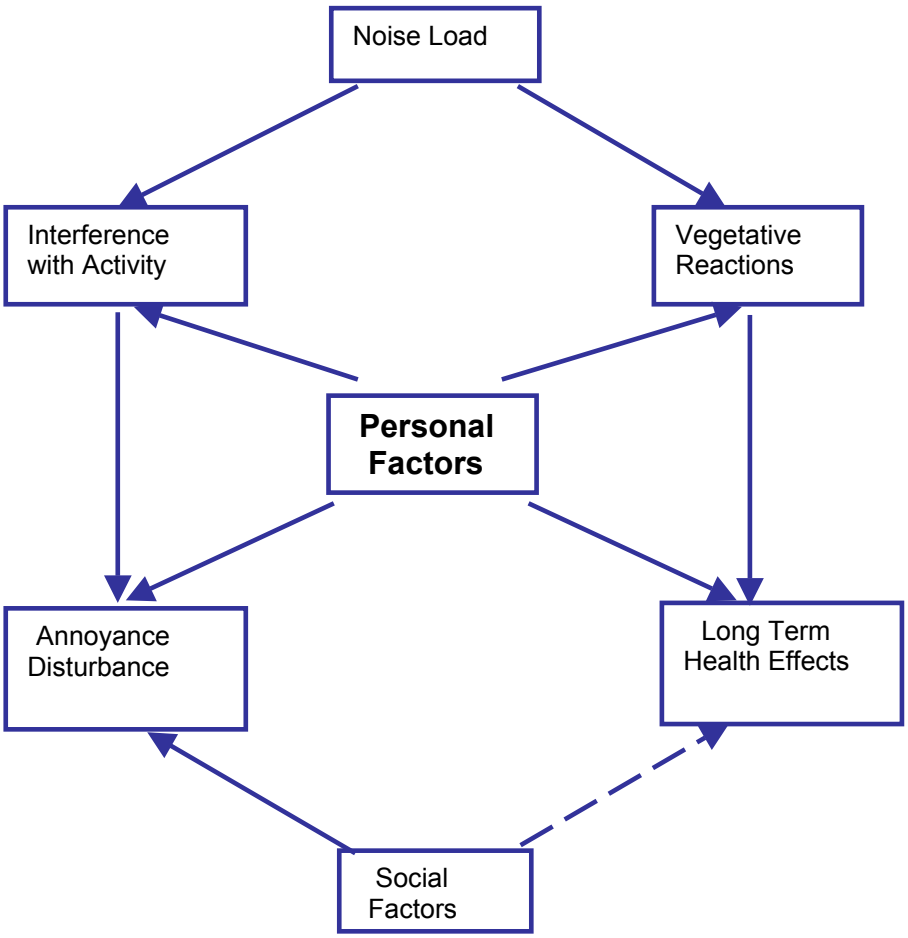

Figure 13. Factors moderating noise annoyance.

8.1.2 Annoyance and the "meaning" of noise. Kalveram (2000) points out that much psychoacoustical noise research has limitations, because it is based upon the correlation between annoyance ratings and physical measurements of sound energy, with subsequent correlation of annoyance and sound level. But equivalent level, A-weighted or linear, is only a part of the total process. Noise level and noise dose approaches neglect the "meaning" of a noise and are contrary to the interactive model in Figure 13. Kalveram proposes an "ecological" approach to noise research, which emphasises the psychological functions of sounds. Annoyance originates from acoustical signals which are not compatible with, or which disturb, these psychological functions. In particular, disturbance of current activities is a primary effect of noise exposure. Kalveram has extended his approach to include "psycho-biological" effects. Annoyance conveys a "possible loss of fitness" (PLOF), which Kalveram links to the message that an individual's Darwinian fitness will decrease if they stay in that situation. Darwinian fitness, in this context, refers to the ability to generate behaviour patterns which permit coping with changes in the environment. For example, to either eliminate a threat or to reduce it to a level which is within the individual's handling capacity. Darwinian fitness may clearly be under threat from noise, to an extent depending on personal factors. A few persons are known to have modified their responses to low frequency noise, thereby removing it from the category of a threat and challenge.

Kalveram summaries the PLOF concept as follows.

"First a harmful variable is assumed to be present in the environment, which affects the individual's (Darwinian) fitness. Then a chance is given that a neural detector will evolve, the input of which is the sensory – here acoustical – stimulation correlated with this harmful variable, while the output is motivating to actions which diminish the sensory input, thereby interrupting current behaviour."

Those who experience long-term exposure to low frequency noise may recognise this process within themselves.

Most field work on noise annoyance has been where there is a known source, for example air or road transport. The particular circumstances of some low frequency noise problems, where the noise source is not known, adds an additional element to annoyance. Those affected suffer extreme frustration and may find it necessary to assume a source, thus enabling themselves to cope through provision of a focus for anger and resentment. Assumed sources have included gas pipelines, radio transmissions and defence establishments.

8.2 Annoyance Measurements. Annoyance measurements are generally of the type described by Kalveram (2000), an attempt to relate annoyance ratings directly to measured noise levels. As described above, these measurements are limited in their results, since they deal with only part of the annoyance complex.

8.2.1 Laboratory determinations. There have been a large number of laboratory determinations of annoyance of low frequency sounds, mainly measurements using either 'normal' or 'sensitive' subjects. Stimuli have included tones, bands of noise or specially developed spectra. There is of course, a wide range of possible stimuli, which experimenters have chosen according to their experience of what is required.(Adam, 1999; Andresen and Møller, 1984; Broner and Leventhall, 1978b; Broner and Leventhall, 1984; Broner and Leventhall, 1985; Goldstein, 1994; Goldstein and Kjellberg, 1985; Inukai et al., 2000; Kjellberg and Goldstein, 1985; Kjellberg et al., 1984; Møller, 1987; Nakamura and Inukai, 1998; Persson and Bjorkman, 1988; Persson-Waye, 1985; Poulsen, 2002; Poulsen and Mortensen, 2002). Some laboratory studies have used recordings of real noises as stimuli, whilst others have worked with the actual noises as experienced by subjects in their own work places or homes. (Holmberg et al., 1993; Landström et al., 1994; Manley et al., 2002; Mirowska, 1998; Tesarz et al., 1997; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Determinations have also been aimed at relating the A-weighted level of the low frequency noise to its annoyance.

8.2.2 Experimental methods. The responses required from subjects vary with experimental method. In laboratory investigations, subjects may be asked to 'imagine' themselves relaxing in their homes in the evening and to rate annoyance by, for example, choice on a semantic scale ranging from 'Not Annoying' to 'Extremely Annoying'. Other methods include marking the level of annoyance on an unnumbered linear scale at a point between 'Not at all

annoying' and 'Very annoying', or assigning a number to a reference noise and appropriate numbers to other noises in order to estimate their magnitudes. These psychological techniques are well established, but need care in their performance, as they are sensitive to experimental factors.

8.2.3 Equal annoyance contours. The main results of this work are as follows. Møller (1987) investigated contours of equal annoyance for pure tones in the frequency range 4Hz to 31.5Hz. The annoyance contours are influenced by the narrowing of the range of equal loudness contours, discussed above. Møller's results are shown in Figure 14. The vertical scale is the annoyance rating in terms of the distance marked for the tone along a 150mm linear scale. The lowest frequencies have to be at a higher level in order to be audible but, once they become audible, their annoyance increases rapidly. For example, the range for 4Hz is about 10dB between extremes. 8Hz and 16Hz have a 20dB range, whilst 31.5Hz has nearly 40dB range. The 1000Hz comparison, which is for an octave band of noise, has a range of nearly 60dB. These findings are important, as they confirm that the hearing contours are reflected in annoyance, although loudness and annoyance are not necessarily the same. Figure 14 gives averages for 18 subjects with normal hearing.

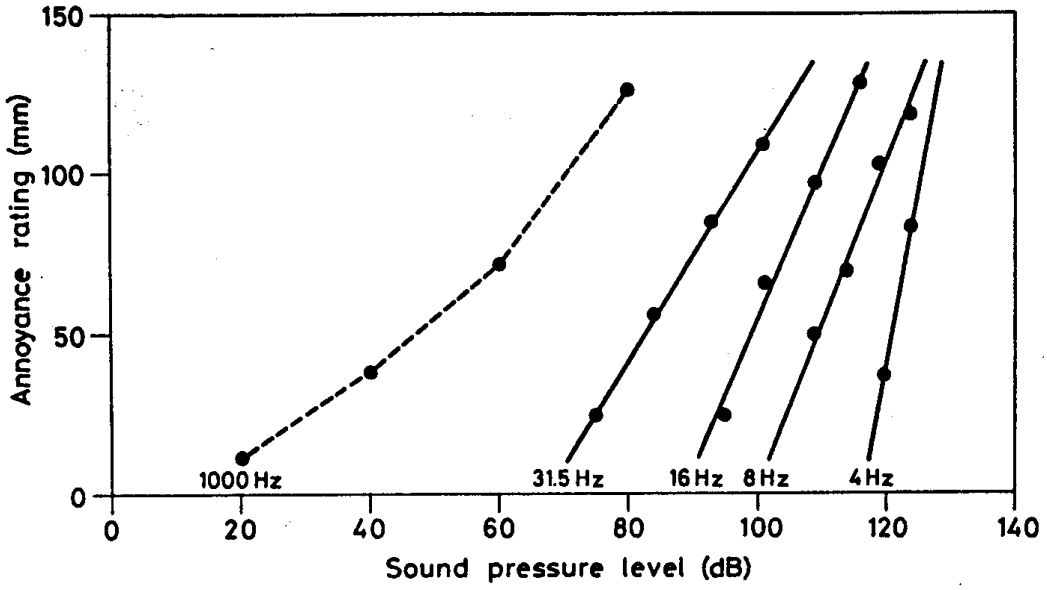

Figure 14. Annoyance rating, showing rapid growth at low frequencies.

8.2.3 Individual annoyance functions. Broner and Leventhall (1978) measured individual annoyance functions for 20 subjects using ten low frequency noise stimuli. The psychophysical function was assumed to be a simple power function

$$\psi = k\varepsilon^{\beta}$$

Where ψ represents the estimation of psychological magnitude, ε is the stimulus intensity and β a subject-specific exponent. It was shown that there was a wide range of individual exponents, β, from a low of 0.045 to a high of

0.4 and three groupings of individual differences were identified. Previous work at higher frequencies had also shown individual loudness functions (Barbenza et al., 1970) and had posed the question of whether one set of regulations should be applied to all people (Bryan and Tempest, 1973).

8.2.4 Annoyance and the dBA. A comparison of a band of noise peaking at 250Hz with a band peaking at 100Hz, whilst both were adjusted to the same A-weighted level, showed that the annoyance from the low frequency noise was greater than that from the higher frequency noise at the same A-weighted level (Persson et al., 1985). This work was subsequently extended (Persson and Bjorkman, 1988; Persson et al., 1990) using a wider range of noises, for example, peaking at 80Hz, 250Hz. 500Hz and 1000Hz, leading to the following conclusions:

There is a large variability between subjects.

The dBA underestimates annoyance for frequencies below about 200Hz.

For broadband low frequency noise, the underestimate was found to be 3dB for levels around 65dB(Linear) and 6dB for levels around 70dB(Linear). Similar results had been obtained in earlier work (Kjellberg et al., 1984). Two broadband noises were investigated, in which one was dominated by energy in the 15-50Hz range. Twenty subjects compared the two noises within the dynamic range 49-86dBA. At equal A-weighted levels, the noise dominated by the low frequency component was perceived as 4-7dB louder and 5-8dB more annoying.

Investigations have also been made to compare the effects on task performance of either 100Hz and 1000Hz. tones or bands of noise centred on 100Hz (~ 2 octaves wide) and 1000Hz(~ 1 octave wide) (Landström et al., 1993). During the experiment the subjects adjusted the tones or noises to levels which they found to be acceptable for performance of the tasks. The results indicated that, when the A-weighted levels were compared, it under-rated the effects of the 100Hz tone by about 14dB, but over-rated the effects of the band of noise centred on 100Hz by 10-15.5dB, depending on sound level. There are clearly differences in the perceptions of tones and bands of noise.

8.2.5 Unpleasantness. The "unpleasantness" of low frequency noise has also been estimated (Inukai et al., 2000; Nakamura and Inukai, 1998). Nakamura and Inukai used a stimulus sound of a pure tone in 20 conditions from 3Hz to 40Hz and pressure levels from 70dB to125dB, with evaluation by 17 subjects. There were four main subjective factors in response to low frequency noise: auditory perception, pressure on the eardrum, perception through the chest and more general feeling of vibration. (In actual problems in the field, a fifth factor is the failure of assessment methods, which intensifies other responses). Analysis of the responses showed that auditory perception was the controlling factor.

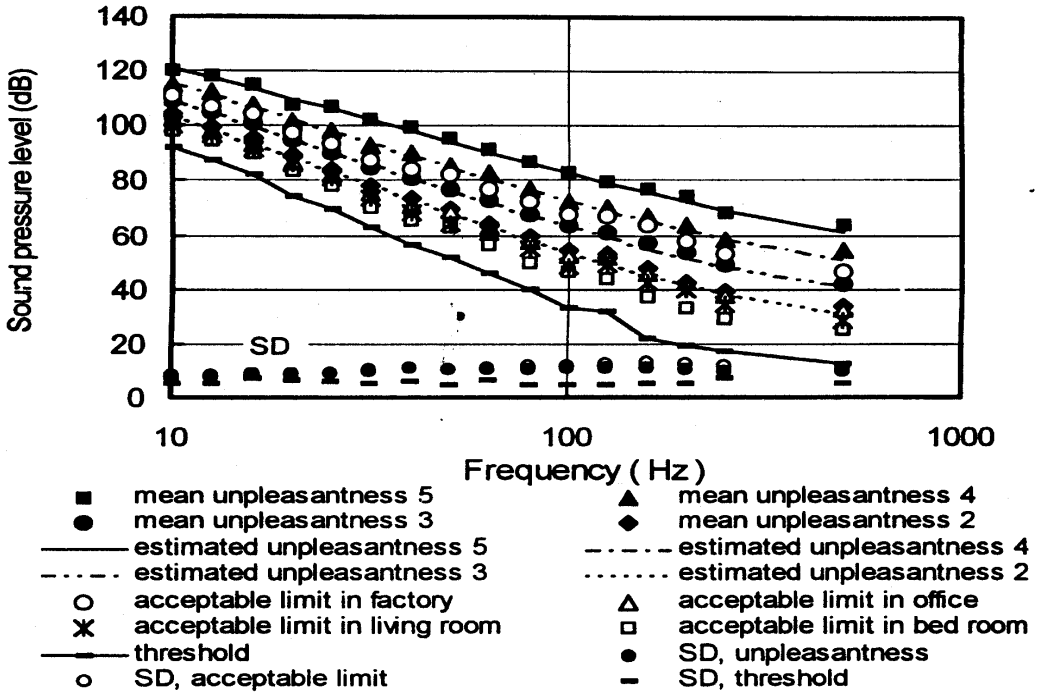

Figure 15. Equal unpleasantness contours and acceptable limits (Inukai).

Inukai et al (2000) determined "equal unpleasantness" contours for 39 subjects over a tone frequency range of 10Hz to 500 Hz (Figure 15). A verbal scale was used ranging through: *Not at all unpleasant (1) - somewhat unpleasant (2) – unpleasant(3) – quite unpleasant(4) – very unpleasant(5)*. Subjects in a test chamber were asked to assume different home and work situations and adjust the level of a tone to match a level on the scale, as requested by the experimenter. For example if instructed to match to level 4 (*quite unpleasant*), subjects would adjust the tone until they judged that this level was reached. Results are shown in Figure 16. The numbers 1,2,3,4,5 refer to the unpleasantness level. All levels of unpleasantness are approximately linear with a slope of 5 - 6dB per octave. The acceptable limits for different locations are all above the hearing threshold in this laboratory setting. For example, the self-adjusted acceptable limit in an assumed bedroom is more than 10dB above threshold, but this might not be replicated for long term night exposure in a real bedroom. This work emphasises the point that a sound which is audible is not necessarily unacceptable.

8.2.6 Spectrum balance The work by Inukai et al (2000) was for single tones. Spectrum balance has also been considered a factor in noise annoyance of a wideband spectrum. Correlation of a number of complaints with the corresponding spectra (Bryan, 1976) led to the conclusion that, for spectra which averaged as shown in Figure 16, a fall off above 32Hz of 5.7dB/octave was acceptable, whilst a fall off from 63Hz at 7.9 dB/octave was unacceptable. Work on acceptable spectra of air conditioning noise in offices led to similar conclusions (Blazier, 1981). Blazier found that, on average, acceptable office environments had a fall off of 5dB/octave. An excess of low frequency noise led to rumble, an excess of mid frequency noise led to roar, whilst an excess of high frequency noise led to hiss. Later work (Blazier, 1997) developed a "Quality Assessment Index" for an HVAC noise through the balance of low, mid and high frequencies.

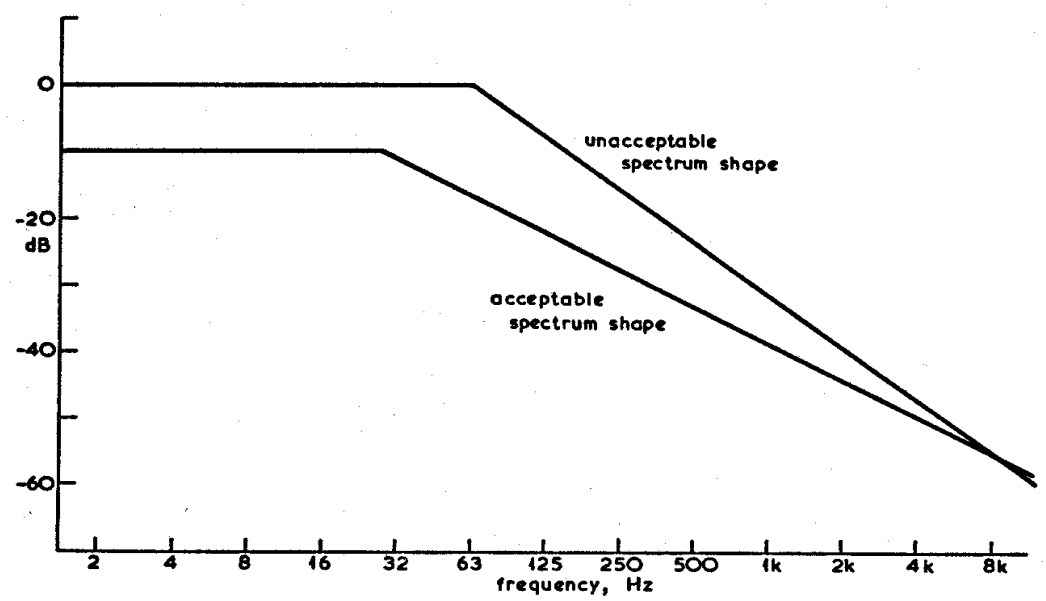

Figure 16. Acceptable and unacceptable spectrum slopes.

A contrary view was given following work on different shapes of spectra (Goldstein and Kjellberg, 1985). It was found that noise which fell by 3dB/octave was more annoying than noise which fell by 6dB/octave or 9dB/octave. This has not been resolved, but Bryan's subjects had long term exposure in real settings, whilst Goldstein and Kjellberg's listened to 10 second samples in the laboratory, so removing any temporal growth of annoyance from the responses. It is also possible that, for the lower rates of fall off, the subjects were responding to the high frequencies in the noise. Goldstein and Kjellberg did show that the A-weighted level underestimates the perceived annoyance of the noises.

8.2.7 **(dBC – dBA) weighting.** The difference between C- and A-weightings has also been considered as a predictor of annoyance (Broner, 1979; Kjellberg et al., 1997), as this difference is an indication of the amount of low frequency energy in the noise. If the difference is greater than 20dB, there is the potential for a low frequency noise problem. Kjellberg et al used existing noise in work places (offices, laboratories, industry etc) with 508 subjects. Three sub- groups were obtained with a maximum difference in low and high frequency exposure. The conclusions on correlations of (dBC – dBA) difference and annoyance were that the difference is of limited value, but, when the difference exceeds 15dB, an addition of 6dB to the A-weighted level is a simple procedure. However, the difference breaks down when the levels are low, since the low frequencies may then be below threshold. The difference cannot be used as an annoyance predictor, but is a simple indicator of when further investigations may be necessary.

8.2.8 **(dBLIN – dBA) weighting.** Disturbance from noise of industrial plants was investigated by Cocchi et al (Cocchi et al., 1992). Comparisons were made of loudness evaluations and various weighted levels and it was suggested that the difference between linear and A-weighting could be used as an assessment. For the spectra investigated, lower values of dBA (20 – 35dBA) correlated with higher (dBLIN - dBA) differences of 20 to 30dB. For high values

of dBA (60 - 70dBA), the difference varied from 10-30dB, but mainly clustered in the 10 – 20dB range. This is possibly because noise with low dBA values might be associated with a higher proportion of low frequencies. Advantages of (dBLIN - dBA) over (dBC – dBA) were not discussed.

8.2.9 Home and work environments. Other work, which has assessed low frequency noise in real or assumed work environments or in the home, has included (Bryan, 1976; Cocchi et al., 1992; Holmberg et al., 1997; Holmberg et al., 1993; Holmberg et al., 1996; Landström et al., 1993; Landström et al., 1994; Lundin and Ahman, 1998; Mirowska, 1998; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Studies of simulated ventilation noise in a test laboratory (Holmberg et al., 1993) showed that, for the same A-weighted levels, a ventilation noise with a spectrum which fell gradually with increasing frequency was more annoying than a noise with a band of raised levels around 43Hz. Difference in acceptable comfort levels was 7dB. It was suggested that an A-weighted criterion for ventilation noise should be 35dBA rather than 40dBA and be lower still for environments designed for intellectual work. However, Landström et al. (1994) investigated subjective adjustments to the frequency of a tone , in order to produce the most and least acceptable frequencies, whilst maintaining the overall level at 40dBA. The majority of subjects chose the most acceptable frequency to be in the 50Hz - 63Hz third octave bands and the least acceptable frequency to be in the 500Hz band. Whilst this may appear to contradict other work, note that very few acceptable frequencies were chosen to be below 50Hz.

Homlberg et al (1996 and 1997) assessed noise in real environments. The 1996 paper compared responses of about 240 subjects with the noise measures which might be available on a sound level meter i.e. dBLIN, dBA, dBB, dBC and dBD and the difference (dBC-dBA). Additionally, Zwicker loudness (ISO532, 1975) and Low Frequency Noise Rating (LFNR) (Broner and Leventhall, 1983) were calculated. There was poor correlation between the sound level meter weightings and annoyance. Similarly, the loudness in sones and the difference (dBC – dBA) did not correlate well. The LFNR did separate out annoying and not annoying noises, but no more effectively than the (dBC – dBA).

8.2.10 Level variations. Holmberg et al (1997) investigated noise in workplaces, using the (dBC – dBA) difference as an indicator. Low frequency noise exposure was found in a group of 35 out of a total of 337 persons. Measurements of temporal variation of the levels of low frequency noise at the workplaces, averaged over 0.5, 1.0 or 2.0 seconds, was correlated with subjective annoyance. Significant correlation was found between the irregularity of the noise levels and annoyance.

This work represents an advance, in that it shows the importance of fluctuations in noise level. A limitation of much work on assessment of low frequency noise has been that long term averaged measurements were used and, consequently, information on fluctuations was lost. Many complaints of low frequency noise refer to its throbbing or pulsing nature. Broner and

Leventhall(1983) had noted the importance of fluctuations and suggested a fluctuation penalty of 3B in the Low Frequency Noise Rating Assessment. The importance of fluctuations has also been assessed in laboratory experiments (Bradley, 1994). Subjects listened first to steady wideband noises which peaked at 31.5Hz and adjusted the overall level of these to be equally annoying to a reference spectrum which fell at 5dB/octave. It was found that the more prominent the low frequency noise, the greater the reduction in level required for equality of annoyance with the reference spectrum. The test spectra were now amplitude modulated, in the low frequency region only, at modulation frequencies of 0.25, 0.5, 1.0, 2.0 and 4.0Hz and depths of 10dB and 17dB. Subjects again adjusted the level of the noises to produce equal annoyance with the (unmodulated) reference noise. The reductions varied with modulation frequency and modulation depth. An example is that, for the highest modulation depth at 2.0Hz modulation frequency, the level was reduced by 12.9dB averaged over the subjects. This work confirms the importance of fluctuations as a contributor to annoyance and the limitation of those assessment methods, which do not include fluctuations in the assessment.

8.2.11 Field investigations. Vasudevan and Gordon (1977) carried out field measurements and laboratory studies of persons who complained of low frequency noise in their homes. A number of common factors were shown:

The problems arose in quiet rural or suburban environments
The noise was often close to inaudibility and heard by a minority of people
The noise was typically audible indoors and not outdoors
The noise was more audible at night than day
The noise had a throbbing and rumbly characteristic
The main complaints came from the 55-70 years age group
The complainants had normal hearing.
Medical examination excluded tinnitus.

These are now recognised as classic "hum" descriptors.

Further work in the laboratory showed that gradually falling spectra, as measured in the field and simulated in the laboratory possessed a rumble characteristic. Figure 17 compares a measured noise on the left with a simulated noise on the right. Both fell at 7 – 8 dB/octave and had similar rumble characteristics. It is also known that a rapidly falling spectrum, such as one which follows the curve of the NR or NC ratings has an unpleasant quality.

This was one reason for the development of the PNC rating as an improvement of the NC rating (Beranek et al., 1971). Further work (Vasudevan and Leventhall, 1982), confirmed that levels close to threshold caused annoyance, which increased if the noise also fluctuated. This work included spectra with tonal peaks and emphasised that the nature (quality) of the noise was important. Fluctuating noises may be far more annoying than predicted by their average sound levels.

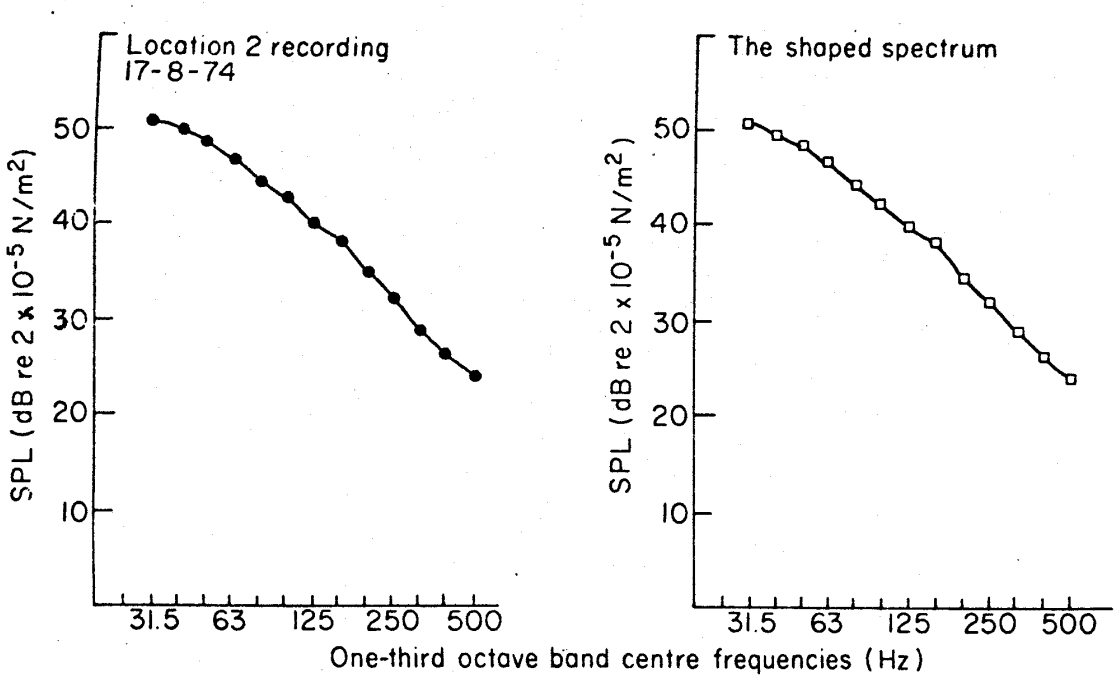

Figure 17. Measured spectrum (left) and simulated spectrum (right).

8.2.12 Inherent fluctuations. A narrow band of noise possesses inherent fluctuations. The band has a central "carrier" frequency at approximately the centre frequency of the band and a randomly fluctuating envelope with a mean frequency of (0.64x bandwidth) (Rice, 1954). This means, for example, that a third octave band of noise at 10Hz, which has a bandwidth of about 2.5Hz, will have amplitude fluctuations of mean frequency 1.6Hz. The amplitude fluctuations follow a Raleigh probability distribution. Physically one can interpret the phenomenon as a beating between components within the noise band and, as the components are of similar amplitude, the amplitude fluctuations are large.

The preceding paragraphs show that both wideband falling noise spectra and narrow band noise spectra may possess rumble characteristics.

8.2.13 Annoyance in homes. Recent work on annoyance to people in their homes has been by Mirowska (1998) and Lundin and Ahman (1998). Both these papers considered annoyance due to plant or appliances, installed in, or adjacent to, living accommodation. Mirowska found problems from transformers in electricity substations, ventilation fans, refrigeration units and central heating pumps. Lundin and Ahman investigated a husband and wife who experienced typical symptoms of aversion to low frequency noise. Refrigerators and freezers were suspected as the source of the offending noise which, in some parts of the building, was high at 50Hz. The time varying pattern of the noise, due to equipment cycling, was considered to add to its annoyance. However, there was no totally convincing link between effects on health and the noise.

9. Effects of low frequency noise on behaviour, sleep periods, task performance and social attitudes

9.1 **Naturally occurring infrasound.** The effects of infrasound generated by storms up to 1500 miles away were investigated in Chicago during May 1967, a period when the weather in Chicago was calm (Green and Dunn, 1968). Statistics on road traffic accidents and school absences indicated higher correlations on days of intense infrasonic disturbances, as compared with days of mild infrasound. The Föhn wind is a warm, dry down-current, which occurs in mountainous areas. It is associated with a sharp temperature rise, decrease in humidity and drop in barometric pressure. (Moos, 1963; Moos, 1964). It is not known whether infrasound has been measured under the conditions of the Föhn wind, but the shearing effects of the wind are potential sources of infrasound. Moos' suggestions, following a study of local statistics, included the following:

- *Pre-Föhn weather has biological effects.*
- *Mortality and birth rates are higher during Föhn periods than under other weather conditions.*

These papers refer to low frequency infrasound of natural occurrence. They are exploratory and have not been followed up by other workers.

9.2 **Low frequency noise and sleep.** Although exposure to low frequency noise in the home at night causes loss of sleep, there is evidence that low frequency noise under other conditions induces short sleep periods (Fecci et al., 1971; Landström and Byström, 1984; Landström et al., 1985; Landström et al., 1991; Landström et al., 1982; Landström et al., 1983).

Fecci et al monitored workers exposed to noise from air conditioning in a laboratory. The noise peaked at 8Hz with a level of 80dB, but also included broadband noise at higher frequencies. It was found, by EEG recording, that subjects exposed to the noise exhibited a much higher percentage of drowsiness than that found in a non-exposed population.

Landström and his colleagues carried out a series of laboratory evaluations of physiological effects of low frequency sound, with particular reference to sleep periods, as detected by EEG recordings. The main conclusions from this work are:

- *Exposure to intermittent noise at 16Hz and a level of 125dB was an effective stimulus of reduced wakefulness*
- *When stimuli at 6Hz and 16Hz were at 10dB below and 10dB above the hearing threshold, the levels above threshold led to a reduced wakefulness. The levels below threshold did not have this effect.*

- *When 10 deaf and 10 hearing subjects were exposed to 6Hz at 115dB for 20 minutes, reduced wakefulness was found amongst the hearing subjects, but not the deaf ones. This indicates that the effects depend on cochlear stimulation, since the noise was above threshold level.*
- *A reduction in wakefulness occurred during a repeating 42Hz signal at 70dB, whilst an increase in wakefulness occurred for a repeating 1000Hz signal at 30dB.*
- *Exposure to ventilation noise with and without tones indicated greater fatigue in the presence of the tone. A masking noise (pink noise) added to the ventilation noise tended to counteract this effect.*

The work by Landström and colleagues shows that low frequency noise above the threshold of hearing leads to reduction in wakefulness. This does not contradict Fecci, although the spectrum for the workers investigated by him was below threshold at the peak of 8Hz, as the spectrum was above the threshold at frequencies greater than 20Hz. Fecci may have been mistaken in attributing the effects he observed to the frequencies below 20Hz.

9.3 Low frequency noise and task performance. The hypothesis that low frequency noise may cause deterioration in the performance of tasks has been tested a number of times (Kyriakides and Leventhall, 1977; Landström et al., 1991; Persson-Waye et al., 2001; Persson-Waye et al., 1997).

Kyriakides and Leventhall used a continuous pointer-following task as the central task, whilst a peripheral task required a response to the onset of lights located both in front of the subject and on the periphery of vision. The test conditions were obtained from: audio frequency noise at 70dBA as the reference, an infrasound noise band from 2Hz to 15Hz at 115dB, an audio frequency noise band from 40Hz to 16kHz at 90dBA, alcohol (94mm^3 of vodka taken with fizzy orange) or a placebo (fizzy orange), combined alcohol and infrasound, combined audible noise and infrasound. The tasks were performed for 36 minutes. Results showed that, under the noise condition, performance was maintained for the central task, but the peripheral task deteriorated. The alcohol, which put subjects into a condition where they failed a breathalyser test, produced deterioration of both the central and peripheral tasks. The effects of infrasound were similar to alcohol in character, but not statistically significant. However, there was an indication that the effect of infrasound increased with time spent on the task.

Landström used figure identification as a test of performance, in which the subject had to identify five different patterns hidden in 15 different figures. Noise exposures were either to broadband ventilation noise, to which a tone at 100Hz, 40dBA, had been added, or to the tone noise with a pink masking noise (50 – 200Hz, 41dBA). The number of correct answers was lower without the masking noise.

Persson Waye et al (1977) assessed effects of low frequency noise on performance in a simulated office environment, in order to study both subjective and objective effects. Two ventilation noises were used, both of the same A-weighted level (41-42dBA) and NC / NR35 rating. One was mid frequency broadband, whilst the other had an added peak at 31.5Hz of 70dB,

as shown in Figure 18. Subjects were selected from those who felt eardrum pressure from low frequency noise. The subjects performed three cognitive tasks under both noise conditions. The work showed that low frequency noise interfered more strongly with performance and that cognitive demands were less well coped with under these conditions. There was an indication of effects developing over time. Effects on mood included a lower social orientation and lowered feeling of pleasantness.

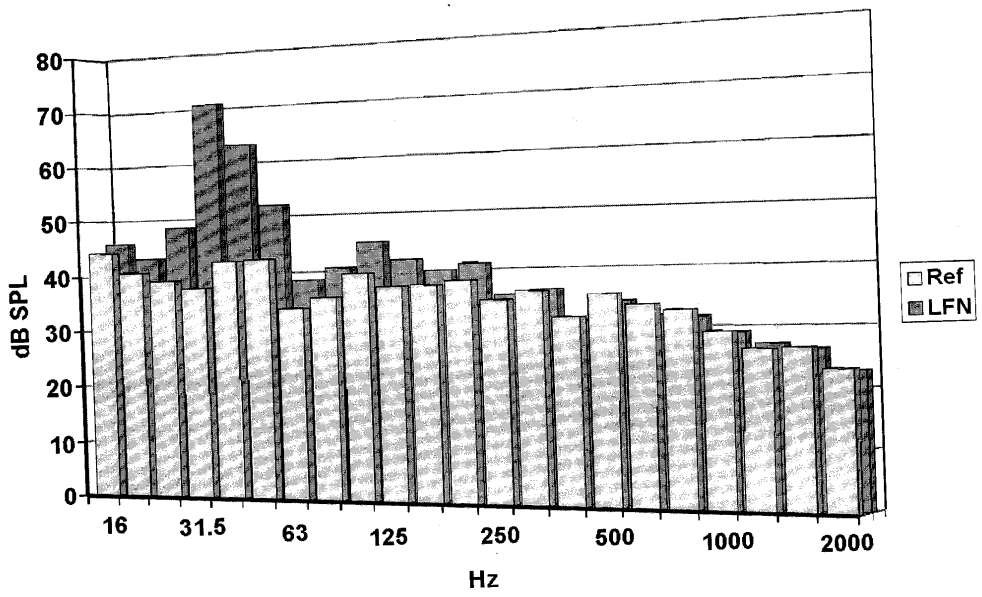

Figure 18. Test spectra, low frequency and mid frequency.

Perrson Waye et al (2001) refined and extended this work in order to answer the following questions:

- *Can low frequency noise, at a level normally present in control rooms and offices, influence performance and subjective well being?*
- *What kind of performance tasks are affected by low frequency noise?*
- *How is the performance affected by duration of exposure?*
- *What is the relation between self rated sensitivity and noise effects?*

A total of 32 subjects, assessed for sensitivity to low frequency noise, took part.18 subjects had high sensitivity to low frequency noise. Three computer-based and one pen and paper based performance tasks were used. Additionally, a questionnaire, to evaluate effort, mood, annoyance, adverse symptoms etc. was completed by the subjects. The results showed that low frequency noise, at levels occurring in office and control rooms, had a negative influence on more demanding verbal tasks, but its effects on more routine tasks was less clear. There was an indication that the low frequency noise was more difficult to ignore or habituate to, which may reduce available information processing resources. The study supports the hypothesis that low frequency noise may impair work performance.

Although these studies were directed at work environments, they have a clear application to effects of low frequency noise in the home.

10. Low frequency noise and stress

Stresses may be grouped into three broad types: cataclysmic stress, personal stress and background stress. Cataclysmic stress includes widespread and devastating physical events. Personal stress includes bereavements and similar personal tragedies. Cataclysmic and personal stresses are evident occurrences, which are met with sympathy and support, whilst their impacts normally reduce with time. Background stresses are persistent events, which may become routine elements of our life. Constant low frequency noise has been classified as a background stressor (Benton, 1997b; Benton and Leventhall, 1994). Whilst it is acceptable, under the effects of cataclysmic and personal stress, to withdraw from coping with normal daily demands, this is not permitted for low level background stresses. Inadequate reserves of coping ability then leads to the development of stress symptoms. In this way, chronic psychophysiological damage may result from long-term exposure to low-level low frequency noise.

Changes in behaviour also follow from long-term exposure to low frequency noise. Those exposed may adopt protective strategies, such as sleeping in their garage if the noise is less disturbing there. Or they may sleep elsewhere, returning to their own homes only during the day. Others tense into the noise and, over time, may undergo character changes, particularly in relation to social orientation, consistent with their failure to recruit support and consent that they do have a genuine noise problem. Their families and the investigating EHO may also become part of their problem. The claim that their "lives have been ruined" by the noise is not an exaggeration, although their reaction to the noise might have been modifiable at an earlier stage.

10.1 Low frequency noise and cortisol secretion. It is difficult to measure stress directly, but cortisol secretion has been used as a stress indicator (Ising and Ising, 2002; Persson-Waye et al., 2002; Persson-Waye et al., 2003). Under normal circumstances, cortisol levels follow a distinct circadian pattern in which the diurnal variation of cortisol is to drop to very low levels during the early morning sleep period, rising towards the awakening time. The rise continues until about 30 minutes after awakening, followed by a fall until midday and further fluctuations. Stress disrupts the normal cortisol pattern.

Ising and Ising (2002) discuss how noise, perceived as a threat , stimulates release of cortisol. This also occurs during sleep, thus increasing the level of night cortisol, which may interrupt recreative and other qualities of sleep. Measurements were made of the effect on children who, because of traffic changes, had become exposed to a high level of night lorry noise. There were two groups of subjects, exposed to high and low noise levels. The indoor noise spectrum for high levels typically peaked at around 60Hz, at 65dB, with a difference of maximum L_C and L_A of 26dB. The difference of average levels was 25dB, thus indicating a low frequency noise problem. Children exposed to the higher noise levels in the sample had significantly more problems with concentration, memory and sleep and also had higher cortisol secretions.

Conclusions of the work were that the A-weighting is inadequate and that safer limits are needed for low frequency noise at night.

Perrson Waye et al (2003), studied the effect on sleep quality and wakening of traffic noise (35dB L_{Aeq}, 50dBL_{Amax}) and low frequency noise (40dBL_{Aeq}). The low frequency noise peaked at 50Hz with a level of 70dB. In addition to cortisol determinations from saliva samples, the subjects completed questionnaires on their quality of sleep, relaxation and social inclinations. The main findings of the study were that levels of the cortisol awakening response were depressed after exposure to low frequency noise and that this was associated with tiredness and a negative mood.

In a laboratory study of noise sensitive subjects performing work tasks, it was found that enhanced salivary cortisol levels were produced by exposure to low frequency noise (Persson-Waye et al., 2002). A finding was that subjects who were sensitive to low frequency noise generally maintained higher cortisol levels and also had impaired performance. A hypothesis from the study is that changes in cortisol levels, such as produced by low frequency noise, may have a negative influence on health, heightened by chronic noise exposure.

The three studies reviewed above show how low frequency noise disturbs the normal cortisol pattern during night, awakening and daytime exposure. The disturbances are associated with stress related effects.

EEG recording has been used to study sleep disturbance by low frequency noise (Inaba and Okada, 1988). Subjects in a sleep laboratory were exposed to levels up to 105dB at 10Hz and 20Hz, up to 100dB at 40Hz and up to 90dB at 63Hz. The effects were assessed by the "sleep efficiency index", which is the ratio of total sleep time to time in bed. Sleep times were determined from continuous EEG recordings. There was little effect for sound levels under 85dB, but reactions for the highest sound levels were significantly greater at 40Hz and 63Hz than for 10Hz and 20Hz.

11. The HUM

11.1 **Occurrence.** The Hum is the name given to a low frequency noise which is causing persistent complaints, but often cannot be traced to a single, or any, source. If a source is located, the problem moves into the category of engineering noise control and is no longer "the Hum", although there may be a long period between first complaint and final solution. The Hum is widespread, affecting scattered individuals, but periodically a Hum focus arises where there are multiple complaints within a town or area. There has been the Bristol Hum (England), Largs Hum (Scotland), Copenhagen Hum (Denmark), Vancouver Hum (Canada), Taos Hum (New Mexico USA), Kokomo Hum (Indiana USA) etc. A feature of these Hums is that they have been publicised in local and national press, so gathering a momentum which otherwise might not have occurred. The concepts of memetics are applicable here. Memetics studies how ideas are spread by "memes", where a meme is defined as a cognitive or behavioural pattern, held in an individual's memory, which is capable of being copied to another individual's memory. As examples, Marsden considers an extreme application (Marsden, 2001) whilst Ross deals with the role of memes in psychosomatic illness (Ross, 1999).

Although the named Hums, such as Kokomo, have gained much attention, they should not be allowed to detract from the individuals who suffer on their own.

11.2 **Hum character.** The sound of the Hum differs between individuals. Even in the areas of multiple complaints, the description is not completely consistent, although this may be because people use different words to describe the same property of a noise. Publicity tends to pull the descriptions together. The general descriptors of the sound of the Hum include: a steady hum, a throb, a low speed diesel engine, rumble and pulsing. A higher pitch, such as a hiss, is sometimes attributed. The effects of the Hum may include pressure or pain in the ear or head, body vibration or pain, loss of concentration, nausea and sleep disturbance. These general descriptions and effects occur internationally, with close similarity.

Unsympathetic handling of the complaint leads to a build-up of stress, which exacerbates the problems. Hum sufferers tend to be middle aged and elderly, with a majority of women. They may have a low tolerance level and be prone to negative reactions. The knowledge that complaints are being taken seriously by the authorities helps to reduce personal tensions, by easing the additional stresses consequent upon not being believed. This is particularly so when, as is often the case, only one person in a family is sensitive to the noise. Whilst some Hum sufferers may have tinnitus, they will, of course, also be troubled by noise at a different frequency from their tinnitus.

11.3 **Psychological aspects.** Psychosocial factors affect the physiological impact of noise (Hatfield et al., 2001). Adverse physiological consequences may be mediated by psychological factors related to the noise exposure. It is plausible that excessive noise exposure promotes negative psychological reactions,

leading to adverse physiological effects, as was shown by Hatfield et al. Therefore, psychological factors must be addressed to help ameliorate the effects of the Hum.

Some Hum sufferers have achieved this for themselves, saying that they have "learnt to live with the Hum" so that it no longer worries them. Others are "cured" by prescription of relaxant drugs. For a few, the Hum goes away after a time. Some escape the Hum by moving house. One long term sufferer, and leading campaigner for official help with low frequency noise problems, decided that it was time to leave the low frequency treadmill and now has no problem, remaining detached from low frequency noise and of the opinion that to become involved with other sufferers heightens ones awareness of the noise. Some sufferers accept that the noises are not at a high level, but that their reactions are equivalent to those which might be expected from a high level of noise – "As soon as I hear the noise, something builds up inside me". This is a similar response to that of hyperacusis sufferers, although more specialised in its triggers. A form of hyperacusis may be indicated.

Combined acoustical and psychological studies (Kitamura and Yamada, 2002) have explored involvement of the limbic system of the brain in the responses.[1] The limbic system commands survival and emotional behaviours, which we cannot always control, although we may learn to do so.

11.4 **Sources.** The Hum remains a puzzling aspect of low frequency noise. No widespread Hum has been unequivocally traced to specific sources, although suspicion has pointed at industrial complexes. At the time of writing, an investigation of the Kokomo Hum is in progress, fully financed by the local authorities.

In the absence of known sources, Hum sufferers often search their neighbourhoods for a source, walking or driving around at night. It is important for them to find a target for their frustrations. Some general ones include the main gas pipelines, radio transmissions (particularly pulsed signals for navigation), defence establishments etc. Gas pipelines have been investigated as a source (Krylov, 1995; Krylov, 1997). It was shown that there are circumstances where turbulence in the pipes could result in ground waves, which might couple with buildings and produce low frequency noise, although this has not been measured. However, a different explanation must be sought in areas remote from pipelines and it is possible that there are a number of unrelated sources, whilst in some cases there may be no sources. There have been other suggestions that the Hum may have its source in ground borne vibrations (Manley et al., 2002; Rushforth et al., 1999).

[1] The human brain has three layers representing its three stages of development. The primitive (reptilian) brain is connected with self preservation. The intermediate (old mammalian) brain is the brain of the inferior animals and related to emotions. This is the limbic system. The superior (new mammalian) brain is related to rational thought and intellectual tasks. The limbic system is activated by perceived threats.

11.5 Auditory sensitivity. Special difficulties arise when, despite persistent complaints, there is no "measurable" noise, or the noise levels at low frequencies are in the 40 - 50dB range, well below threshold. van den Berg supports tinnitus as an explanation in these circumstances (van den Berg, 2001). With respect to audibility, the average threshold levels must be interpreted carefully. van den Berg's choice of a limit criterion is the low frequency binaural hearing threshold level for 10% of the 50 – 60 year old population, which is 10-12 dB below their average hearing level (van den Berg and Passchier-Vermeer, 1999a). This may be too strict, since 10% of the age group has more sensitive hearing. For example, in England, which has a population of about 49,000,000, there are nearly 5,000,000 in the 50 – 59 year age group (see www.statistics.gov.uk). Thus, 500,000 of this age group in England will be more sensitive than the suggested cut-off for perception of low frequency noise. Yamada et al (1980) found one subject to be 15dB more sensitive than the average, whilst recent work (Kitamura and Yamada, 2002), gives two standard deviations from the average threshold as about 12dB. However, the average threshold of the complainants in this work is somewhat higher than the ISO 226 threshold. A range of two standard deviations covers 95% of people, Based on Kitamura and Yamada, three standard deviations, assuming a random distribution, is given by 18dB from the average threshold and covers 99% of the population. The remaining 1% includes 0.5% who are more sensitive than the three standard deviation limit and 0.5% less sensitive than this limit, at the opposite side of the average threshold. 0.5% of the population of England is about 245,000 persons, whilst 0.5% of the 50 – 60 year age group is about 25,000 people, who might have very sensitive low frequency hearing. A "rule of thumb" may be to take 15 - 20dB below the ISO 226 threshold as the cut off for perception, but this is a very generous level, depending on the complainants hearing level at low frequencies.

Advice on how to approach problems of the Hum is given in Section 14.

12. Surveys of occurrence and effects

In a catalogue of 521 social surveys (Fields, 2001), there are four which are specific to low frequency noise. Two of these are for clearly identified transport sources - air and rail – two are for noise from other sources (Mirowska and Mroz, 2000; Persson and Rylander, 1988) However, a number of additional surveys, either not listed by Fields or too recent for inclusion, have also been carried out (Møller and Lydolf, 2002; Persson-Waye and Bengtsson, 2002; Persson-Waye and Rylander, 2001; Tempest, 1989; Yamada et al., 1987).

12.1 Complaint surveys

12.1.1 Sweden. Persson and Rylander (1988) surveyed all the 284 local authorities in Sweden with respect to complaints from heat pumps, heavy traffic and fan and ventilation installations. These three sources were 71% of all noise complaints, comprising 42% ventilation systems, 20% heavy traffic, 9% heat pumps. Where there had been an increase in complaints over time, heat pumps and ventilation systems were the main problems. A recent follow-up (Persson-Waye and Bengtsson 2002) investigated changes over a 14 year period from 1988 by questioning a random selection of 41 environmental authorities, including 11 from districts with less than 50,000 inhabitants, 10 with 50,000 to 100,000 inhabitants and 11 with greater than 100,000 inhabitants. Low frequency noise represented 44% of the noise complaints, although some authorities had no complaints of low frequency noise, whilst one had over 200.

The sources of low frequency noise are shown in Figure 19.

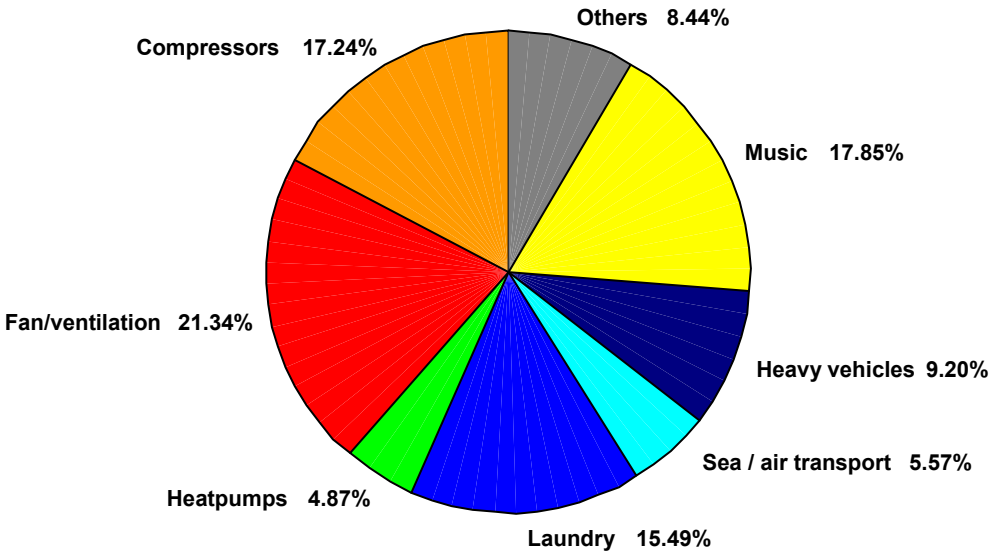

Figure 19. Percentages of sources causing complaints

This follow-up study showed a relative reduction of low frequency noise complaints compared with total noise complaints – 44% compared with 71%. This was thought to be due to a higher number of general noise complaints or to the limited selection of environmental authorities. Most of the authorities preferred assessment of low frequency noise by third octave analysis in preference to the use of A-weighting.

12.1.2 UK. Tempest (1989) conducted a survey amongst 242 UK local authorities, which was 50% of the total number. There was an 87% response (210) and 453 complaints of low frequency noise identified in the two year period covered by the survey. The distribution of complaints between categories is shown in Figure 20. It will be noted, in this UK survey, that there are very few internal sources. The conclusions of the survey were that, in the UK, there may be 526 complaints of low frequency noise a year and positive identification is made in 88% of cases. This leaves over 60 complaints a year which are potentially in the "Hum" unsolved category.

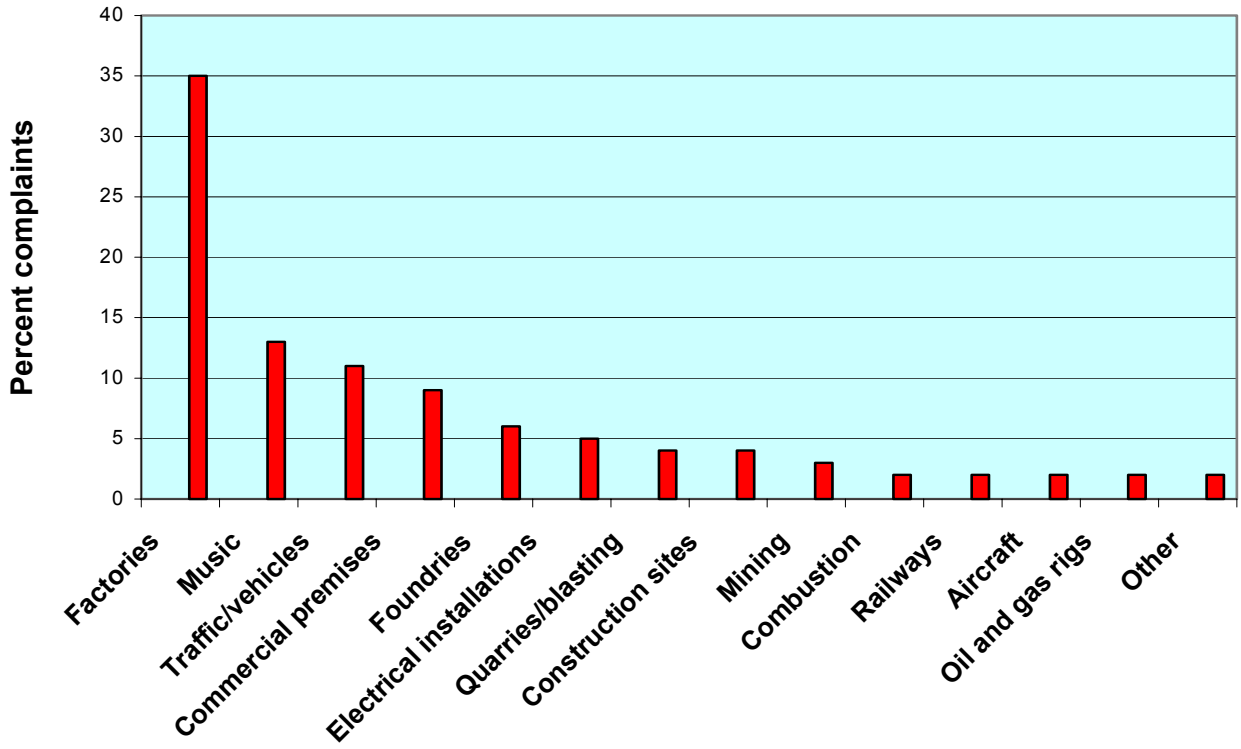

Figure 20. Complaint categories (Tempest 1989).

12.1.3 **Japan.** A database of low frequency noise problems has been established in Japan by collecting the results of published work (Yamada et al., 1987). 206 datasets were obtained giving personal details, including individual threshold measurements, the type of complaint and measured levels. Some main points from the survey are:

At the lower frequencies, below 16Hz, the levels which cause complaints of rattling of light-weight building components are below the hearing threshold.

The minimum measured threshold is 10-15dB below the average threshold.

12.1.4 **Denmark.** An extensive survey of individual complainants has been carried out in Denmark (Møller and Lydolf, 2002). 198 fully completed questionnaires were returned. The survey was detailed, containing 45 questions. The main results are:

Descriptions of the sound: Humming, rumbling, constant and unpleasant, pressure in ears, affects whole body, sounds like large idling engine, coming from far away.

Where and when heard: Mainly indoors at home (81.8%), some experience the noise outside, particularly close to home, only a slight preponderance for night time awareness.

Sensory perception: 92.9% heard the noise through their ears. Others were aware of it but did not register the noise as a sound. There was some vibration perception either through the body and by feeling vibration in buildings.

Time before trouble starts. Respondents were asked how long it was between awareness of the sound and adverse reactions to it. For over 60% it started immediately. About 25% required a few minutes awareness, 6% required ½ to 1 hour. A small percentage took longer.

Do other people hear or sense the sound? Nearly 40% were the only ones who perceived the sound. Nearly 30% said that just a few other persons did so, whilst 14% claimed that everybody did.

Type of effects. There were multiple effects. Disturbance while falling asleep (77.2%). Awakened from sleep (53.8%). Frequent awareness (68%). Frequent irritation (75.1%). Disturbed when reading (61.9%). The sound is a torment (76.1%).

Other troubles. Insomnia (67.5%). Dizziness (29.4%). Headaches (40.1%). Palpitation (41.1%). Lack of concentration (67%). Other effects (39.1%).

12.2 **Effects on health.** In an epidemiological survey of low frequency noise from plant and appliances in or near domestic buildings, the focus was on health effects (Mirowska and Mroz, 2000).

Percentages of exposed adults and the sources were as in Table 4.

Noise source	L_A dB	Percentage people exposed	Kind of exposure
Fans	26 – 31	33	Day, intermittent
Central heating pumps	23 – 33	18	Night, day intermittent
Transformers	20 – 23	30	Continuous
Refrigeration units	21 - 32	19	Night, day intermittent

Table 4. Noise exposures in survey.

In 81% of the test flats, levels were below the 25dBA night and 35dBA day criteria.

A control group of dwellings had comparable conditions to the test group, with similar A-weighted levels, except that there was no low frequency noise. There were 27 individuals in the test group and 22 in the control group.

The test group suffered more from their noise than the control group did, particularly in terms of annoyance and sleep disturbance. They were also less happy, less confident and more inclined to depression.

The comparison of the symptoms between the tested group and the control group show clear differences, as in Table 5.

Symptom	Test group %	Control group %
Chronic fatigue	59	38
Heart ailments anxiety, stitch, beating palpitation	81	54
Chronic insomnia	41	9
Repeated headaches	89	59
Repeated ear pulsation, pains in neck, backache	70	40
Frequent ear vibration, eye ball and other pressure	55	5
Shortness of breath, shallow breathing, chest trembling	58	10
Frequent irritation, nervousness, anxiety	93	59
Frustration, depression, indecision	85	19
Depression	30	5

Table 5. Health comparison of exposed and control group.

These results are extremely interesting as an epidemiological survey of an affected and a control group. Table 5 shows very adverse effects from low frequency noise levels which are close to the threshold and which do not exceed A-weighted limits.

Other work has investigated a group of 279 persons exposed to noise from heat pump and ventilation installations in their homes (Persson-Waye and Rylander, 2001). The experimental groups were 108 persons exposed to low frequency noise and 171 non-exposed controls. There was no significant difference in medical or psycho-social symptoms between the groups. This

work did show that the prevalence of annoyance and disturbed concentration and rest was significantly greater among the persons exposed to low frequency noise. The A-weighted levels did not predict annoyance.

Effects of low frequency noise have also been investigated in the laboratory using the same subjects performing intellectual tasks, with and without low frequency noise in the noise climate, but at the same A-weighted level. It has been shown that, after the exposure session with low frequency noise, the subjects were less happy and recorded a poorer social orientation. (Persson-Waye et al., 1997).

12.3 Defra survey. The survey carried out in conjunction with this report for Defra was deliberately kept simple, asking a few questions as follows, in addition to personal details:

- *Date the noise was first heard*
- *Where the noise is heard*
- *The type of location*
- *Is there a suspected source?*
- *What does the noise sound like*
- *When is the noise heard most?*
- *What are the effects on you?*

Additional comments were also invited.

The distribution of survey forms was to known complainants of low frequency noise who had joined a pressure group: the Low Frequency Noise Sufferers Association, the Noise Abatement Society or the UK Noise Association. About 700 survey forms were distributed and 157 were returned. Some of the returns were not from genuine "hum" sufferers as they knew the source of the noise, for example traffic from a nearby busy roundabout, a nearby commercial or manufacturing establishment, vehicle reversing signals at a nearby supermarket goods-in area, a gunnery range, a police helicopter at night etc. However, they are people who react strongly to noise.

Main conclusions from the survey are:

12.3.1 Age range of complainants.

Below 25	none
26 – 35	0.65%
36 – 45	3.8%
46 - 55	15.9%
56 – 65	24.8%
66 – 75	32.5%
Above 75	12.7%
Unknown	9.5%

There is a clear increase with age. These figures are for men and women combined. Nearly two thirds of the respondents were female.

12.3.2 Where the noise is heard most

Generally in the home (Including the bedroom)	65%
House and garden	21%
Mainly the bedroom	8.9%
Outside only	1.9%
Only in the living room	1.3%
At a neighbours	0.65%
At the office	0.65%
Not given	0.65%

The great majority, about 95%, hear the noise in and around their homes.

12.3.3 When is the noise heard most?

At night only	48.4%
All the time	29.9%
Daytime	7%
Irregular	5%
Low background noise	3.2%
Evening	3%
Morning	1.3% (continued)
Depends on the wind	1.3%
Not given	1.9%

The majority , 78.3%, hear the noise all the time (including night) or at night only.

12.3.4 What does the noise sound like?

There were varied responses to this question. Over 20 different descriptions were given, ranging from the familiar "hum" to morse code dots, jiggling rattles and explosions. However, by combining similar responses, the following were produced.

Hum	39.5%
Pulsing	21.6%
Engine and similar	22.3%
Vibration	1.9%
Other	14.2%

The "engine and similar" group is made up of "engine, machinery, rumble and throb".

83.4% hear a hum, a pulsing or an engine. The engine is typically described as an idling diesel.

12.3.5 Is there a suspected source? The source was sometimes local and well known to the complainant. However, others were unable to suggest the source of their noise.

A total of 37 returns did not know the source. 30 returns blamed the gas supply system, but this response may have been partly due to previous publicity. The remaining 90 returns gave a wide range of sources, usually local.

12.3.6 Type of location. The respondents lived in a range of locations, spread widely across the UK. Rural, coastal, urban and suburban locations were included.

12.3.7 What is the effect of the noise on you? The effects were a close parallel to those in the Møller and Lydolf survey described above. Pain or pressure in the ears and head, sleep disturbance, irritation, body vibration and nausea were all present. A small number had habituated to the noise, so that they were no longer disturbed. One considered it as an intriguing, but harmless, curiosity.

13. General Review of Effects of Low Frequency Noise on Health[1]

The results of a recent survey of complaints about infrasound and low frequency noise on 198 persons in Denmark (Møller and Lydolf, 2002) revealed that nearly all reported a sensory perception of sound. They perceived the sound with their ears, but many mentioned also the perception of vibration, either in their body or in external objects. The sound disturbs and irritates during most activities, and many considered its presence as a torment to them. Many reported secondary effects, such as insomnia, headache and palpitation. These findings support earlier reports in the published literature.

13.1 **Historical**. Almost thirty years ago in a review paper of the effects of infrasound on man (Westin, 1975) drew attention to the fact that the amount of natural and man-made infrasound that man is subjected to is larger than is generally realised. He stated that the few studies that have concerned themselves uniquely with the physiological effects of moderate-to-high levels of infrasound exposure (as opposed to audible sound or vibration exposures) have failed to demonstrate significant effects on man other than those concerning the inner ear and balance control. But the existing studies indicate that inner ear symptoms due to moderate-to-high levels of infrasound may be more common than is generally appreciated. At very high sound pressure levels (greater than 140dB), ear pain and pressure become the limiting factors. Direct evidence of adverse effects of exposure to low-intensity signals (less than 90dB) is lacking.

Harris et al. (Harris et al., 1976) were of the opinion that the claims that infrasound adversely affects human performance, makes people “drunk” and directly elicits nystagmus, have not been clearly demonstrated in any experimental study. The effects obtained at low intensity levels of 105 to 120dB, if they can be substantiated at all, have been exaggerated. Recent well-designed studies conducted at higher intensity levels have found no adverse effects of infrasound on reaction time or human equilibrium. The levels at which infrasound becomes a hazard to man are still unknown. Previously, (Slarve and Johnson, 1975) had exposed four male subjects to infrasound ranging from 1 through 20Hz for a period of 8 minutes up to levels of 144dB. There was no objective evidence (including audiograms) of any detrimental effect of infrasound. However, all subjects experienced painless “pressure build-up” in the middle ear that was relieved by valsalva manoeuvre or by cessation of infrasound, and voice modulation and body vibration consistently occurred. They concluded that infrasound pressures as high as 144dB are safe for healthy subjects, at least for periods of 8 minutes, and they predicted that longer periods would also be safe. Borredon (Borredon, 1972) exposed 42 young men to 7.5Hz at 130 dB for 50 minutes. This exposure caused no adverse effects. The only statistically significant change reported among the

[1] This section was contributed by Dr P L Pelmear

many parameters measured was an insignificant (< 1.5 mm Hg) increase in the minimal arterial blood pressure. However, Borredon also reported that several of his subjects felt drowsy after the infrasound exposure.

13.2 Effects on humans. Infrasound exposure is ubiquitous in modern life. It is generated by natural sources such as earthquakes and wind. It is common in urban environments, and as an emission from many artificial sources: automobiles, rail traffic, aircraft, industrial machinery, artillery and mining explosions, air movement machinery including wind turbines, compressors, and ventilation or air-conditioning units, household appliances such as washing machines, and some therapeutic devices. The effects of infrasound or low frequency noise are of particular concern because of its pervasiveness due to numerous sources, efficient propagation, and reduced efficiency of many structures (dwellings, walls, and hearing protection) in attenuating low-frequency noise compared with other noise.

In humans the effects studied have been on the cardiovascular and nervous systems, eye structure, hearing and vestibular function, and the endocrine system. Special central nervous system (CNS) effects studied included annoyance, sleep and wakefulness, perception, evoked potentials, electroencephalographic changes, and cognition. Reduction in wakefulness during periods of infrasonic exposure above the hearing threshold has been identified through changes in EEG, blood pressure, respiration, hormonal production, performance and heart activity. Infrasound has been observed to affect the pattern of sleep minutely. Exposure to 6 and 16 Hz levels at 10 dB above the auditory threshold have been associated with a reduction in wakefulness (Landström and Byström, 1984). It has also been possible to confirm that the reduction on wakefulness is based on hearing perception since deaf subjects have an absence of weariness (Landström, 1987).

In moderate infrasonic exposures, the physiological effects observed in experimental studies often seem to reflect a general slowdown of the physiological and psychological state. The reduction in wakefulness and the correlated physiological responses are not isolated phenomena and the physiological changes are considered to be secondary reactions to a primary effect on the CNS. The effects of moderate infrasound exposure are thought to arise from a correlation between hearing perception and a following stimulation of the CNS. The participation of the reticular activating system (RAS) and the hypothalamus is thought to be of great importance. Taking this into account, changes in the physiological reactions are not just a question of whether the sound waves are above the hearing threshold. Furthermore reactions within the CNS, including RAS, hypothalamus, limbic system, and cortical regions are probably highly influenced by the quality of the sound. Some frequencies and characters of the noise are probably more effective than others for producing weariness.

A high degree of caution is necessary before ascribing the origin of physiological changes in working situations to infrasonic exposure because of their association. When analysing the factors promoting fatigue e.g. driving, many aspects have to be considered. The environment is usually a combination of many factors such as seat comfort, visibility, instrumentation,

vibration and noise. However, it is an important fact that in many situations e.g. transport operations, there is a high degree of prolonged monotonous low frequency noise stimulation. This could be crucial in inducing worker fatigue and thereby constitute a safety hazard. Thus although exposure to infrasound at the levels normally experienced by man does not tend to produce dramatic health effects, exposure above the hearing perception level will produce symptoms including weariness, annoyance, and unease. This may precipitate safety concerns in some environmental and many work situations (Landström and Pelmear, 1993).

The primary effect of infrasound in humans appears to be annoyance. (Andresen and Møller, 1984; Broner, 1978a; Møller, 1984). To achieve a given amount of annoyance, low frequencies were found to require greater sound pressure than with higher frequencies; small changes in sound pressure could then possibly cause significantly large changes in annoyance in the infrasonic region (Andresen and Møller, 1984). Beginning at 127 to 133dB, pressure sensation is experienced in the middle ear (Broner 1978a). Regarding potential hearing damage Johnson (Johnson, 1982) concluded that short periods of continuous exposure to infrasound below. 150dB are safe and that continuous exposures up to 24 hours are safe if the levels are below 118dB.

13.3 Biological effects on humans, In the numerous published studies there is little or no agreement about the biological activity following exposure to infrasound. Reported effects include those on the inner ear, vertigo, imbalance etc.; intolerable sensations, incapacitation, disorientation, nausea, vomiting, bowl spasm; and resonances in inner organs, such as the abdomen and heart. Workers exposed to simulated industrial infrasound of 5 and 10Hz and levels of 100 and 135dB for 15 minutes reported feelings of fatigue, apathy and depression, pressure in the ears, loss of concentration, drowsiness, and vibration of internal organs. In addition, effects were found in the CNS, cardiovascular and respiratory systems (Karpova et al., 1970). In contrast, a study of drivers of long distance transport trucks exposed to infrasound at 115 dB found no statistically significant incidence of such symptoms (e.g. fatigue, subdued sensation, abdominal symptoms, and hypertension (Kawano et al., 1991).

Danielson and Landstrom (Danielsson and Landstrom, 1985) exposed twenty healthy male volunteers to infrasound in a pressure chamber and the effects on blood pressure, pulse rate and serum cortisol levels of acute infrasonic stimulation were studied. Varying frequencies (6, 12, 16Hz) and sound pressure levels (95, 110, 125dB) were tested. Significantly increased diastolic and decreased systolic blood pressures were recorded without any rise in pulse rate. The increase in blood pressure reached a maximal mean of about 8 mm Hg after 30 minutes exposure. Lidstrom (Lidstrom, 1978) found that long-term exposure of active aircraft pilots to infrasound of 14 or 16Hz at 125dB produced the same changes. Additional findings in the pilots were decreased alertness, faster decrease in the electrical resistance of the skin compared to unexposed individuals, and alteration of hearing threshold and time perception.

In several experiments to assess cognitive performance during exposure to infrasound (7 Hz tones at 125, 132, and 142dB plus ambient noise or a low frequency noise up to 30 minutes), no reduction in performance was observed in the subjects (Harris and Johnson, 1978). Sole exposure to infrasound at 10 to 15Hz and 130 to 135dB for 30 minutes also did not produce changes in autonomic nervous function (Taenaka, 1989). The ability of infrasound (5 and 16Hz at 95dB for five minutes) to alter body sway responses suggested effects on inner ear function and balance (Tagikawa et al., 1988).

To study vestibular effects in humans, both a rail-balancing task and direct nystagmus (involuntary eye movements) measurements have been used. In the balancing task subjects were required to balance on narrow rails while being presented with various acoustic stimuli. The task results indicated that humans were affected in the audible range as low as 95dB. For frequencies of 0.6, 1.6, 2.4, 7 and 12Hz, aural stimulation at levels as high as 14 dB, either monaural or bilateral, did not significantly affect rail-task performance (Harris, 1976; von Gierke, 1973). However, Evans (Evans and Tempest, 1972) examining the effect of infrasonic environments on human behaviour found that 30% of normal subjects exposed to tones of 2 – 10Hz through earphones at SPLs of 120 – 150Hz had nystagmus within 60 seconds of exposure to the 120dB signal, with 7Hz being most effective in causing it. Higher intensities resulted in faster onset of nystagmus, but there were no complaints of discomfort from any of the subjects at any SPL. Subsequently, Johnson (Johnson, 1975), who investigated nystagmus in many experiments under different conditions with aural infrasound stimulations from 142 to 155dB had negative results. For example, an investigator stood on one leg with his eyes closed, listening aurally to 165dB at 7Hz and 172dB at 1 to 8Hz (frequency sweep) without effect.

Research on the effect of infrasound on mental performance has also shown negative results. For example, infrasound at 125dB (7Hz) did not significantly affect subjects' ability to perform a serial search, a mental task requiring searching and linking pairs of numbers together into a progression (Harris and Johnson, 1978). Because of the lack of CNS effects in controlled studies, the reports of fatigue, drowsiness, or sleepiness have generally been discounted as unimportant. ACGIH believes these are the consequence of the simple relaxation effects of infrasound rather then any adverse health effect (ACGIH, 2001).

Although the effects of lower intensities 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 judgements 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; and 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. Intense low frequency noise appears to produce clear symptoms including respiratory impairment and aural pain. 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 (Berglund et al., 1996).

13.4 Infrasound studies in laboratory animals. The results of some animal studies reporting adverse effects from infrasound exposure may be relevant for indicating possible human health effects. The following studies would seem to be of interest.

a) Vascular - Myocardium

Alekseev (Alekseev et al., 1985) exposed rats and guinea pigs (5 test animals, 2 controls per group) to infrasound (4 to 16Hz) at 90 to 145dB for 3 h/day for 45 days; and tissues were collected on days 5, 10, 15, 25, and 45 for pathomorphological examination. A single exposure to 4 to 10 Hz at 120 to 125dB led to short-term arterial constriction and capillary dilatation in the myocardium. Prolonged exposure led to nuclear deformation, mitochondrial damage and other pathologies. Effects were most marked after 10 to 15Hz exposures at 135 to 145dB. Regenerative changes were observed within 40 days after exposure.

Gordeladze (Gordeladze et al., 1986) exposed rats and guinea pigs (10 animals per group) to 8Hz at 120dB for 3 h/day for 1, 5, 10, 15, 25, or 40 days. Concentrations of oxidation-reduction enzymes were measured in the myocardium. Pathological changes in myocardial cells, disturbances of the microcirculation, and mitochondrial destruction in endothelial cells of the capillaries increased in severity with increasing length of exposure. Ischemic foci formed in the myocardium. However, changes were reversible after exposure ceased.

Rats and guinea pigs exposed to infrasound (8 or 16Hz) at 120 to 140dB for 3 h/day for 1 to 40 days showed morphological and physiological changes in the myocardium. (Nekhoroshev and Glinchikov, 1991)

- Conjunctiva

Male rats (10 /group) exposed to infrasound (8Hz) at 100 and 140dB for 3 h/day for 5, 10, 15, or 25 days showed constriction of all parts of the conjunctival vascularture within 5 days (Svidovyi and Kuklina, 1985). Swelling of the cytoplasm and the nuclei of the endotheliocytes accompanied the decrease in the lumen of the capillaries. The capillaries, pre-capillaries, and arterioles became crimped. Morphological changes were reported in the vessels after exposure for 10, 15, and 25 days. After 25 days, increased permeability of the blood vessels led to swelling of tissues and surrounding capillaries and to peri-vascular leukocyte infiltration. Significant aggregates of formed elements of the blood were observed in the large vessels.

b) Liver

Infrasound exposure damaged the nuclei apparatus, intracellular membrane, and mitochondria of rat hepatocytes in vivo (Alekseev et al., 1987). Infrasound (2, 4, 8, or 16Hz) at 90 to 140 dB for 3 h/day for 40 days induced histopathological and morphological changes in hepatocytes from rats on days

5 to 40. Infrasound (8Hz) at 120 to 140dB induced pathological changes in hepatocytes from the glandular parenchyma and sinusoids.

Morphological and histochemical changes were studied in the hepatocytes of rats and guinea pigs exposed to infrasound (2, 4, 8, or 16Hz) at 90, 100, 110, 120, 130 or 140dB for 3 h/day for 5 to 40 days (Nekhoroshev and Glinchikov, 1992a). Hepatocytes showed increased functional activity, but exposures for 25 and 40 days induced irreversible changes. Changes were more pronounced at 8 and 16Hz than at 2 and 4Hz. Exposures impaired cell organoids and nuclear chromatin. Single exposures did not induce any changes in the hepatocytes and small blood vessels.

c) Metabolism

(Shvaiko et al., 1984) found that rats exposed to 8Hz at 90, 115, or 135dB exhibited statistically significant changes in copper, molybdenum, iron, and/or manganese concentrations in liver, spleen, brain, skeletal muscle, and/or femur compared to concentrations in the tissues of controls. Practically all tissues showed significant changes in all the elements for exposures at 135dB. Changes included elevations and depressions in concentrations. The trends were consistent with increasing sound pressure except for some tissue copper values.

d) Auditory

(Nekhoroshev, 1985) exposed rats to noise of frequencies 4, 31.5, or 53Hz at 110dB for 0.5 h, 3 h, or 3 h/day for 40 days. Infrasound exposure caused graver changes than exposure to sound at 31.5 or 53Hz. Changes observed after exposure to this acoustic factor included reduced activity of alkaline phosphotase in the stria vascularis vessels and their impaired permeability. Impaired labyrinthine hemodynamics led to neurosensory hearing impairment.

(Bohne and Harding, 2000) sought to determine if noise damage in the organ of Corti was different in the low- and high-frequency regions of the cochlea. Chinchillas were exposed for 2 to 432 days to a 0.5 (low-frequency) or 4kHz (high-frequency) octave band noise at 47 to 95dB sound pressure level. Auditory thresholds were determined before, during and after noise exposure. The cochlea's were examined microscopically, missing cells were counted, and the sequence of degeneration was determined as a function of recovery time (0 – 30 days). With high-frequency noise, primary damage began as small focal losses of outer hair cells in the 4-8kHz region. With continued exposure, damage progressed to involve loss of an entire segment of the organ of Corti, along with adjacent myelinated nerve fibres. With low-frequency noise, primary damage appeared as outer high cell loss scattered over a broad area in the apex. With continued exposure, additional apical hair cells degenerated, while supporting cells, inner hair cells, and nerve fibres remained intact. Continued exposure to low-frequency noise also resulted in focal lesions in the basal cochlea that were indistinguishable from those resulting from high-frequency noise.

In guinea pigs, low-frequency pressure changes have been shown to cause head and eye movements (nystagmus) of the animals for square wave pulses with pressure above 150 dB (Parker et al., 1968).

e) Brain

(Nishimura et al., 1987) suggested from experiments on animals that infrasound influences the rat's pituitary adreno-cortical system as a stressor, and that the effects begin at sound pressure levels between 100 and 120 dB at 16Hz. The concentration of hormones shows a slight increase with exposure to infrasound. In the task performance a reduction was seen in the rate of working. It seems probable that concentration was impaired by infrasound exposure.

(Nekhoroshev and Glinchikov, 1992b) exposed rats and guinea pigs (3 per sex per dose level) to 8Hz at 120 and 140dB for 3 hours or 3 h/day for 5, 10, 15, 25, or 40 days and they showed changes in the heart, neurons, and the auditory cortex increasing in severity with increasing length of exposure. The presence of hemorrhagic changes are attributed mostly to the mechanical action rather than to the acoustic action of infrasound. They suggested that the changes in the brain may be more important than in the ears.

f) Lung

Histopathological and histomorphological changes were determined in the lungs of male albino mice exposed to infrasound (2, 4, 8, or 16Hz) at 90 to 120dB for 3 h/day for up to 40 days (Svidovyi and Glinchikov, 1987). After prolonged exposure to 8 Hz at 120 dB sectioned lungs revealed filling of acini with erythrocytes and thickening of inter-alveolar septa; after prolonged exposure to 8 and 16Hz at 140dB sectioned lungs revealed ruptured blood vessel walls, partially destroyed acini, and induced hypertrophy of type-II cells.

13.5 Discussion. No medical condition has been reported in the literature (Tierney Jr et al., 2003) to be associated with the perception of infrasound or its enhancement, but many of the symptoms reported by complainants with perceived or actual infrasound exposure are associated with human disease.

Sleep disorders – getting to or staying asleep, intermittent wakefulness, early morning awakening or combinations of these are common in depression and psychiatric disorders, particularly manic. And they are associated with abuse of alcohol, heavy smoking, stress, caffeine, physical discomfort, daytime napping, and early bedtime.

Headache – chronic headaches are commonly due to migraine, tension or depression but may be related to intracranial lesions, head injury, cervical spondylosis, dental or ocular disease (glaucoma), temporo-mandibular joint dysfunction, sinusitis, hypertension and a wide variety of general medical disorders. By enquiry of precipitating factors, timing of symptoms, and progression most may be distinguished. Those associated with neurological symptoms need a cranial MRI or CT scan, however, about one third of brain tumours present with a primary complaint of headache. With brain tumours and abscesses the clinical presentation is variable and is primarily determined by

anatomical location, proximity to the ventricles, and major alterations in the intracranial pressure dynamics secondary to the mass.

Vertigo – is the cardinal symptom of vestibular (ear) disease. Local causes include perilymphatic fistula, endolymphatic hydrops (Meniere's disease), labrynthitis, acoustic neuroma, ototoxicity, vestibular neuronitis, and vestibular migraine. Central causes include brainstem vascular disease, tumours of the brain stem and cerebellum, multiple sclerosis and vertebrobasilar migraine.

Nystagmus – common causes include Meniere's disease, labrynthitis (with hearing loss and tinnitus), transient following changes in head position, vertigo syndrome due to central lesions e.g. brainstem vascular disease, arteriovenous malfunctions, tumour of the brainstem and cerebellum, multiple sclerosis, and vertebrobasilar migraine.

Nausea and vomiting – this may be caused by a) visceral efferent stimulation – mechanical e.g. gastric outlet obstruction, peptic ulcer, malignancy, small intestine obstruction, adhesions, Crohn's disease, carcinomatosis etc.; dysmotility by medications, small intestine scleroderma, amyloidosis; peritoneal irritation; infections; hepatic disorders; cardiac and urinary disease. b) CNS disorders – vestibular; tumours; infection; and psychogenic (bulimia). c) irritation of chemoreceptor – antitumor chemotherapy; drugs; radiotherapy; pregnancy; hypothyroid and parathyroid disease.

Mental changes – nervousness, excitability, etc., which may be caused by underlying endocrine disorders e.g. hyperthyroidism, menopause, and vitamin deficiencies.

Hallucinations (usually auditory) – may be persistent or recurrent without other symptoms and are usually associated with delirium or dementia. Alcohol or hallucinogens are often the cause.

Hence in the evaluation of subjects with symptoms, which may be attributable to infrasound exposure, a full clinical examination and assessment needs to be undertaken to exclude any other primary or secondary cause.

13.6 **Conclusion.** There is no doubt that some humans exposed to infrasound experience abnormal ear, CNS, and resonance induced symptoms that are real and stressful. If this is not recognised by investigators or their treating physicians, and properly addressed with understanding and sympathy, a psychological reaction will follow and the patient's problems will be compounded. Most subjects may be reassured that there will be no serious consequences to their health from infrasound exposure and if further exposure is avoided they may expect to become symptom free.

14. Complaint procedures

Complaints of low frequency noise must be handled with sincerity and compassion, recognising that low frequency noise is an area of complex subjective diversity. An unsympathetic approach compounds the problems of the complainant, who may already be feeling distressed, disbelieved and isolated. This is especially so when complainants are the only one in their homes who hear the noise.

14.1 **UK advice.** Advice on how to approach investigation of a complaint is as follows. (Casella-Stanger, 2002).

The investigator's first visit should be handled with particular care and the complainant must be shown respect. The situation should be approached with an open mind in order to avoid any entrenched reaction to the complainant.

Continue to keep an open mind during the investigation. Discuss the problem with the complainant and obtain a history and background to it. The history should include the following.

- *When the noise was first heard*
- *Type of noise heard*
- *Duration and frequency of occurrence of the noise*
- *Complainant's belief about the source*
- *Effects of noise on the complainant*
- *Whether other family members hear the noise*
- *Whether the complainant believes he/she is particularly sensitive to other sources of noise.*

14.1.1 **Investigation procedure.** A flow chart of a typical investigation is given in Figure 21. One unfortunate outcome of unsympathetic handling may be that the complainant is transferred from noise specialist to medical specialist and back to noise specialist, whilst both maintain that they can find no basis for the complaint.

At the present time, some complainants of low frequency noise in the UK consider that they are inadequately served by Environmental Health Officers (Benton and Yehuda-Abramson, 2002; Guest, 2002). This is because of a perception of inadequate training in low frequency noise problems, inadequate equipment and a reliance on A-weighting for assessment, leading to frequent conclusions of "not a Statutory Nuisance". This is not the fault of the EHO's who have to work within the current legislation and with the equipment with which they are provided. These problems produce a sense of isolation in the complainant, with attendant elevation of anxiety. The authorities might view the resulting behaviour as inappropriate, but from the complainant's view it is the most rational and best they can achieve.

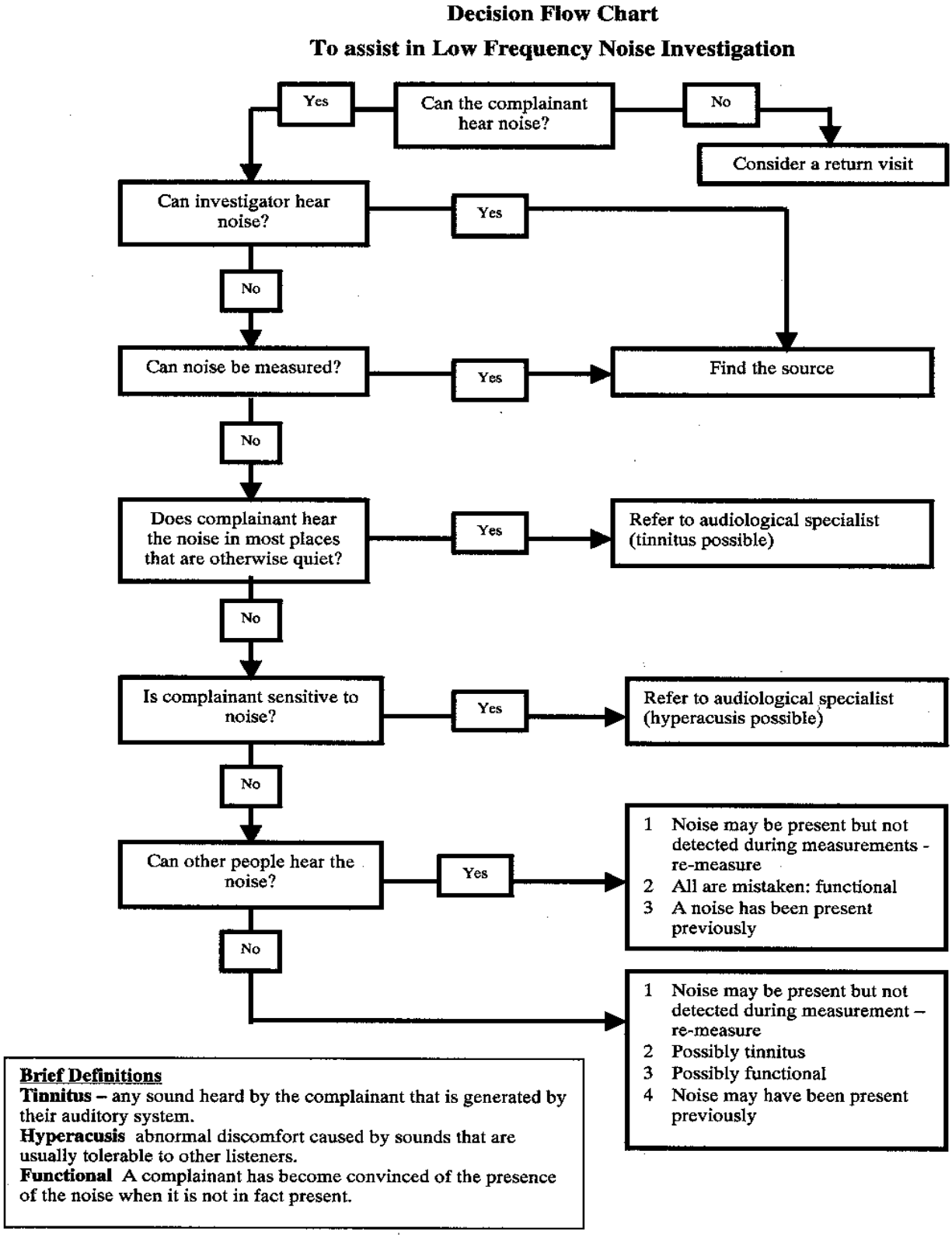

Figure 21. Flow chart of low frequency noise investigation.

14.2 Dutch advice. In the Netherlands, the Environmental Protection Agency of the Rotterdam region has adopted a structured approach to low frequency noise problems (Sloven, 2001). Support is provided for those who are called in to investigate low frequency noise, since the sporadic nature of the complaints means that there are few specialists.

Depending on how the complaint comes in, a typical procedure may be as follows. An inspector from the Environmental Protection Agency (technical aspects and management) contacts the appropriate Municipal Health Service (psychological and social aspects). They work together through a protocol similar to that in Figure 20 to determine whether the problem is "source orientated" or "person orientated".

The investigation is terminated when either the source is located and the problem solved, or if it is decided that the complainant is confused and needs alternative help. Termination may also occur for the following reasons:

- *Levels are very low and the source not determinable without excessive effort*
- *The source is known, but not controllable e.g. traffic*
- *Experience is that similar cases have not been solvable*
- *The complainant has multiple problems, others more severe than the low frequency noise*
- *The complainant refuses co-operation or decides to move house.*

The Dutch approach is interesting, as it makes use of both technical and social specialists, working together to obtain a rounded picture of the problem.

Technical assessment is based on the hearing level exceeded by 5% of the Dutch 55 year old population. Sloven notes that the average age of complainants of low frequency noise is 55, with two thirds female. This is similar to the experience of other countries, but Sloven adds that, for all environmental complainants in the Netherlands (20,000 a year), 70% are women with an average age of about 55, so that the pattern of low frequency noise complaints is not unusual. He also notes that, in about the year 2015, half of the Dutch population will be over 55 years of age.

15. Limits and Criteria

In setting criterion limits it is implicit that these are at levels which protect a certain percentage of the population. Noise levels at which protection is offered typically leave 10-20% of the population annoyed by a noise, since the desire to improve the environment is moderated by technical and economic factors. However, as there is a weak relation between the annoyance of low frequency noise in the home and its level, there may be an argument for more protective criteria for low frequency noise than those which are recommended for other noises (Benton, 1997a).

15.1 Development of criteria. Detailed criteria for environmental low frequency noise have developed over the past 25 years, driven by specific problems, particularly gas turbine installations, which radiate high levels of low frequency noise from their discharge. (Challis and Challis, 1978). Existing criteria from that time are reviewed by Challis and Challis. All criteria for low frequency noise seek to limit the low frequencies to a greater extent than would be permitted by general environmental noise criteria such as Noise Rating (NR), (Kosten and van Os, 1962), which is shown in Figure 22.

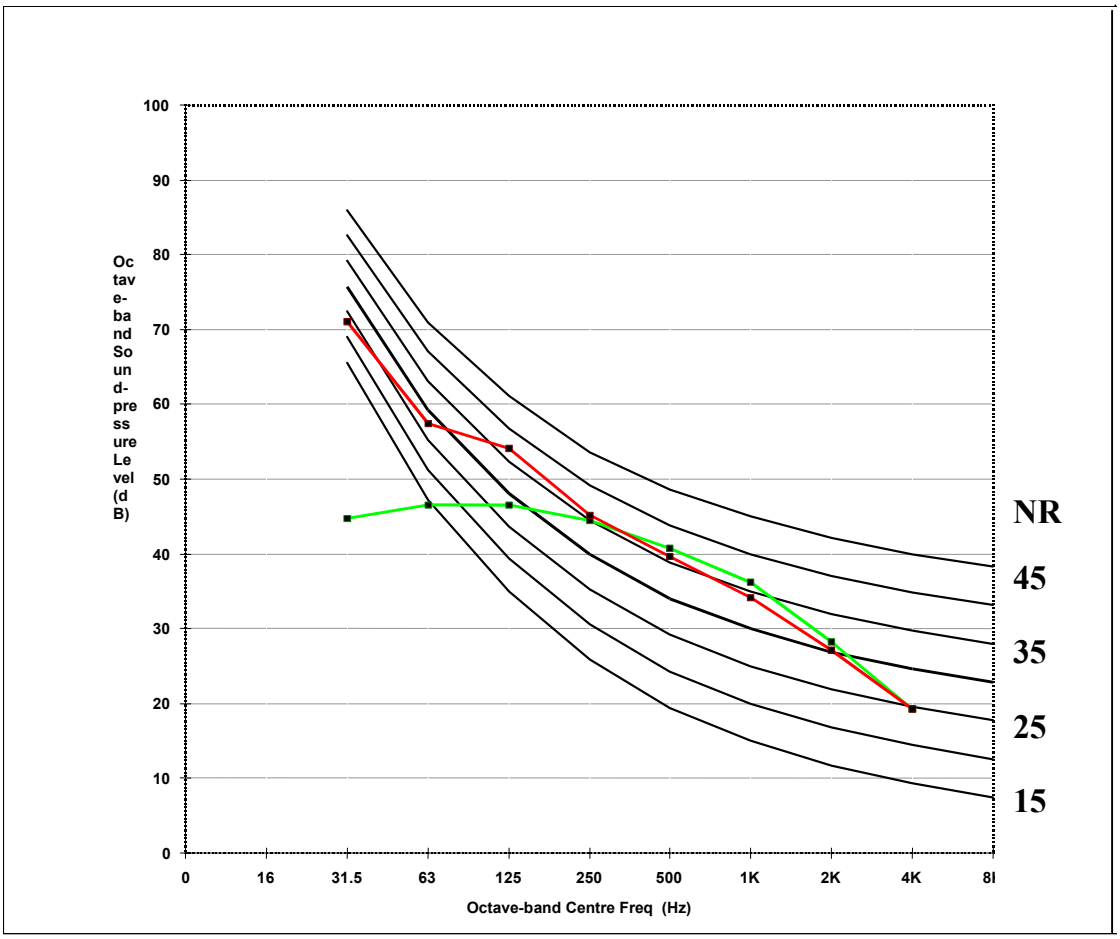

Figure 22. Noise Rating Curves. The two spectra of Figure 18 are plotted, showing how spectra with different subjective effects may have a similar NR number, in this case a little more than NR35.

For example, at low levels of mid-frequency noise, typical low frequency criteria permit a rise in noise levels of about 40dB between 8kHz and 31.5Hz, compared with about 60dB rise for NR 15. Most of the additional reduction is in the low frequency bands. Challis and Challis proposed a set of modified NR curves (NRM) following this pattern and extended down to 16Hz. Noise Rating is not suitable for use with those spectra which have high levels of low frequency noise. In fact, the spectra on which it was tested by Kosten and van Os were deficient in low frequency noise.

15.2 **Sound level meter weighting.** A sound level meter weighting curve was developed for low frequency noise assessment, as in Figure 23. (Inukai et al., 1990) The weighting curves pass more low frequencies through the sound level meter than the A-weighting does, giving them a greater influence on the overall sound level meter reading.

Both the LF curve and the LF2 curve rise in the region of 40Hz. In the LF2 curve, this is by about 10dB, which represents a selective penalty in the region of 40Hz.

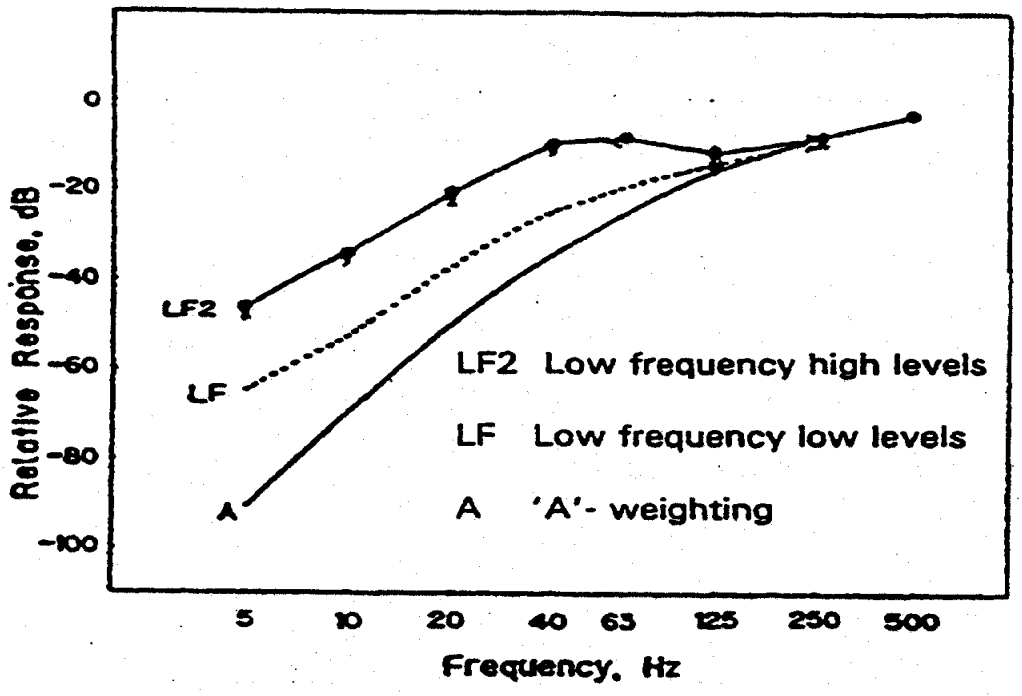

Figure 23. Sound level meter low frequency weighting networks.

15.3 **LFNR Curves.** Similar results had been found by Broner and Leventhall (1983) in work which was based on experiments with subjects judging annoyance of 10Hz wide bands of low frequency noise from 25Hz to 85Hz centre frequencies. It was found that there was a peak in annoyance in the bands with centre frequencies 35Hz and 45 Hz, showing that these bands were more annoying than the lower or higher frequency bands. A similar result had been obtained earlier (Kraemer, 1973). Broner and Leventhall used their results to modify the NR curves in the low frequency region, leading to the LFNR curves,

which impose low frequency penalties as shown in Figure. 24. The curves are similar to NR curves down to 125Hz, but are more restrictive at lower frequencies. The curves are used in the following way.

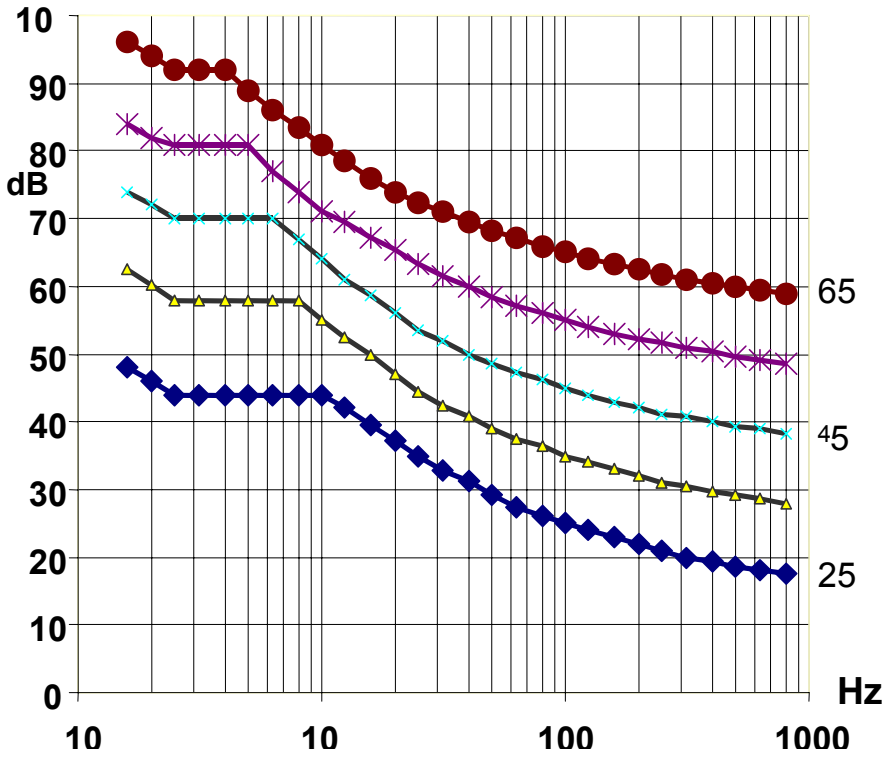

Figure 24. Low frequency noise rating curves LFNR. Each point is at a third octave frequency.

Plot the noise spectrum on the curves and, for frequencies above 125Hz, determine the appropriate rating curve in the normal way. If the spectrum of frequencies below 125Hz exceeds this rating curve, there is the potential for a low frequency problem. The curves assess not only the level of the noise, but also its spectrum balance. A penalty of 3dB was suggested for a noise which was fluctuating. The LFNR curves have not been widely adopted, but it is known that they have been used by some UK local authorities.

15.4 **Low frequency A-weighting.** Another approach to low frequency limits (Vercammen, 1989; Vercammen, 1992) uses a reference curve related to the average threshold minus two standard deviations. Vercammen also suggests using the G-weighting for infrasound, an A-weighting of the range 10Hz to 160Hz (LF_A) for low frequencies and the normal A-weighting for higher frequencies. The following are proposed as typical interior criterion levels.

Measurement	Day	Evening	Night
L_A	35	30	25 dBA
L_G	86	86	86 dBG
LF_A	30	25	20 dBA

It is not possible to make a direct measurement of LF_A by filtering the input to a sound level meter, as the specification of low frequency A-weighting permits wide tolerances. Consequently, third octave band levels are taken from 10Hz to 160Hz and summed for their A-weighting. Vercammen also notes the problems of assessing fluctuations in noise level.

15.5 National Criteria. The interest in criteria for low frequency noise and pressure from complainants, who have felt badly served by the regulatory authorities, has led to a number of countries developing criteria for assessment of low frequency noise problems. The criteria are summarised below:

15.5.1 Sweden. Recommendations for assessment of indoor low frequency noise (Socialstyrelsen-Sweden, 1996) are shown in the Criterion column of Table 6, which also includes the ISO 226 threshold. It is clearly the intention that the lowest frequencies shall not be audible to the average person. However, measurements are of the equivalent noise level (averaged over time) in the third octave band, so missing some of the annoying characteristics of a noise – fluctuations, rumble etc. The averaged level is appropriate to a steady tone, but has limitations for other noises. In the application of this method, the noise may be considered a nuisance if its level exceeds the criterion curve in any third octave band.

Frequency 1/3 octave band Hz	Criterion dB	ISO 226 threshold dB
31.5	56	56.3
40	49	48.4
50	43	41.7
63	41.5	35.5
80	40	29.8
100	38	25.1
125	36	20.7
160	34	16.8
200	32	13.8

Table 6. Swedish limits for low frequency noise

15.5.2 Netherlands. This method, which is intended to determine audibility is based on the average low frequency hearing thresholds for an otologically unselected population aged 50 – 60 years, where the reference levels are the binaural hearing threshold for 10% of the population. That is, the 10% most sensitive. The age range of 50 - 60 years was chosen as typical of the age of complainants. (N S G, 1999; van den Berg and Passchier-Vermeer, 1999a). Comparing 50% levels for 50 – 60 year olds with those of young persons, Table 7 shows that the older people are taken as 7dB less sensitive, on

average, than the younger ones. At the 10% level they are 3dB less sensitive. Information is not given on whether, at lower percentage levels e.g. 5% or 1%, this difference reduces further. The 10% curve is used by considering noise levels exceeding those in the NSG reference curve in the range 20Hz to 100Hz, in order to draw conclusions on their audibility.

The above method is for audibility, not annoyance. A Dutch proposal for annoyance (Sloven, 2001) uses a criterion curve which is close to the German threshold below 40Hz and then corresponds with the Swedish method.

Low frequency hearing threshold for levels for 50% and 10% of the population.
(NSG reference curve in bold)

	Otologically Unselected Population 50 – 60 years		**Otologically Selected Young adults (ISO 226)**	
Freq Hz	**50% dB**	**10% dB**	**50% dB**	**10% dB**
10	103	92	96	89
12.5	99	88	92	85
16	95	84	88	81
20	85	**74**	78	71
25	75	**64**	66	59
31.5	66	**55**	59	52
40	58	**46**	51	43
50	51	**39**	44	36
63	45	**33**	38	30
80	39	**27**	32	24
100	34	**22**	27	19
125	29	18	22	15
160	25	14	18	11
200	22	10	15	7

Table 7. NSG reference curve

15.5.3 Denmark. This method is similar to a proposal of Vercammen, above, in that the G-weighted levels, the A-weighted levels in the 10Hz to 160Hz third octave bands and the normal A-weighting are used (Jakobsen, 2001). Criteria are then as in Table 8 for internal noise levels.

	Infrasound L_{pG}	Low frequency noise $L_{pA,LF}$	Normal noise limit L_{pA}
Dwelling, evening and night	85dB	20dB	30dB / 25dB
Dwelling, day	85dB	25dB	30dB – day and evening
Classroom, office etc	85dB	30dB	40dB
Other rooms in enterprises	90dB	35dB	50dB

Table 8. Danish recommendations

The levels in Table 8 for infrasound are intended to make the G-weighted noise inaudible, being set at 10dB below the G-weighting for the average threshold. There is conjunction at about 16Hz between 85dBG and 20dBA, as shown in Figure. 6 (Section 4.1.1). In the operation of the limits, the noise is measured over a 10 minute period and a 5dB penalty added for impulsive noise e.g. single blows from a press or drop forge hammer. Rumble or similar fluctuation characteristics are not considered and will be averaged out in the 10 minute measurement period.

15.5.4 Germany. This method (DIN:45680, 1997), is based on investigations in the region of industrial installations (Piorr and Wietlake, 1990). Hearing threshold levels used in DIN 45680 are given in Table 9, showing that the thresholds are close to those of ISO 226. The difference (dBC - dBA) > 20dB is used as an initial indication of the presence of low frequency noise. The noise is then measured in third octaves over specified time periods and compared with the threshold curve in Table 9. The main frequency range is from 10Hz to 80Hz. Frequencies of 8Hz and 100Hz are used only if the noise has many components within the range 10Hz to 80Hz. However, there is an assumption in DIN 45680 that the great majority of low frequency noise problems from industrial sources are tonal and that 8Hz and 100Hz third octave bands will be used only rarely. If the level in a particular third octave band is 5 dB or more above the level in the two neighbouring bands, the noise is described as tonal. For tonal noises, the level of the tone above the hearing threshold is found. The day time limit for exceedance of the threshold curve is 5dB in the 8Hz – 63Hz bands, 10dB in the 80Hz band, and 15dB in the100Hz band. In the night period all the limits are reduced by 5dB.

Third octave band frequency Hz	Hearing threshold dB	ISO 226 threshold dB
(8)	(103)	--
10	95	--
12.5	87	--
16	79	--
20	71	74.3
25	63	65.0
31.5	55.5	56.3
40	48	48.4
50	40.5	41.7
63	33.5	35.5
80	28	29.8
(100)	(23.5)	25.1

Table 9. Hearing threshold DIN 45680

For non-tonal noises, the limit for the A-weighted equivalent level (10 Hz – 80 Hz) is 35 dB during daytime and 25 dB during the night, where the A-weighting is obtained by using only the third octave bands which exceed the hearing threshold. Contributions from levels below the threshold are disregarded.

15.5.5 Poland. This method (Mirowska, 2001) uses the frequency range 10Hz to 250Hz. The sound pressure levels of the third octave bands of the noise are compared with a reference curve $L_{A10,}$ derived from $L_{A10} = 10 - k_A$, where k_A is the value of the A-weighting for the centre frequencies of the third octave bands and is negative over the low frequency region. Thus, the L_{A10} curve is 10dB greater than the absolute value of the A-weighting corrections and any single frequency which met the curve will have a level of 10dBA. The curve is shown in Table 10 where it is compared with the ISO 226 threshold. The reference curve is below the ISO 226 threshold at the lower frequencies.

Frequency Hz	L_{A10} dB	ISO 226 dB
10	80.4	
12.5	83.4	
16	66.7	
20	60.5	74.3
25	54.7	65.0
31.5	49.3	56.3
40	44.6	48.4
50	40.2	41.7
63	36.2	35.5
80	32.5	29.8
100	29.1	25.1
125	26.1	20.7
160	23.4	16.8
200	20.9	13.8
250	18.6	11.2

Table 10. Polish reference levels L_{A10}.

The Polish method also takes background noise into account by determining the difference between the sound pressure levels of the noise and the background noise. Consequently there are two components in the assessment:

ΔL_1 - the difference between the measured sound pressure level and the L_{A10} curve.
ΔL_2 - the difference between the sound pressure levels of the noise and the background noise.

The noise is considered to be annoying when:
$\Delta L_1 > 0$
ΔL_2 > 10dB for tonal noise or 6dB for broadband noise

15.6 Comparison of methods.

15.6.1 Criterion curves. The National assessment methods compare the low frequency hearing threshold, or a function related to it, with the problem noise. Where A-weighting is used, there is an assumption that this weighting reflects hearing sensitivity at low frequencies. However, as the A-weighting is loosely

based on what was considered to be the 40 phon loudness contour in the mid 1930's, it has a lower slope than the threshold. Figure 6 shows how the 20dBA curve crosses the threshold at about 30Hz, where the 20dBA curve denotes the levels of tones which will individually register as 20dBA. The reference curves are compared in Table 11. Poland requires the lowest levels and is 10dB lower than Denmark, since one is based on 10dBA and the other on 20dBA. The Netherlands and Germany use an assumed hearing threshold as their reference. Sweden describes a limiting noise curve, which should not be exceeded in any band. This curve is similar to ISO 226 between 31.5Hz and 50Hz, beyond which it tends towards 20dBA.

None of the methods assesses fluctuations, although Denmark imposes a penalty for impulses. The methods are generally designed for assessment of steady tones, but will underrate the subjective consequences of fluctuations, which are the main complaint of many sufferers.

	Poland	**Germany**	**Netherlands**	**Denmark Night**	**Sweden**	**ISO 226**
Frequency Hz	**L_{A10} dB**	**DIN 45680 dB**	**NSG dB**	**20dBA**	**dB**	**dB**
8		103				
10	80.4	95		90.4		
12.5	83.4	87		93.4		
16	66.7	79		76.7		
20	60.5	71	74	70.5		74.3
25	54.7	63	64	64.7		65.0
31.5	49.3	55.5	55	59.4	56	56.3
40	44.6	48	46	54.6	49	48.4
50	40.2	40.5	39	50.2	43	41.7
63	36.2	33.5	33	46.2	41.5	35.5
80	32.5	28	27	42.5	40	29.8
100	29.1	23.5	22	39.1	38	25.1
125	26.1			36.1	36	20.7
160	23.4			33.4	34	16.8
200	20.9				32	13.8
250	18.6					11.2

Table 11. Comparison of reference curves.

15.6.2 Measurement positions. A-weighted levels for assessment of environmental noise are normally taken outside a residential property. The complexities of low frequency noise, including uncertainties in the transmission loss of the structure and resonances within rooms, require low frequency noise to be assessed by internal measurements. This is recognised in the assessment procedures.

There is a measurement uncertainty, which is inversely proportional to both the bandwidth of the analysis and to the duration of the measurement (i.e. the integration time). As a result, the measurement period using a given third octave filter is related to the required accuracy. If the standard deviation of repeated measurements shall be less then 0.2 dB an integration time of almost five minutes is needed at 10 Hz. At 40 Hz a one-minute integration time is necessary and at 1000 Hz two seconds are needed. The noise signal is assumed to be stable over the measurement time, but this is not always so in practise.

16. Validation of the Methods

Piorr and Wietlake (1990) used a night reference curve identical to DIN 45680 up to 63Hz. They reported that 90% of complainants were satisfied with the implementation of the limits. Subsequently, Piorr and Wietlake's night criterion was applied to investigations in the UK (Rushforth et al., 2002) and found to be a "reasonably good predictor of annoyance".

Laboratory measurements using recordings of actual noises (Poulsen, 2002; Poulsen and Mortensen, 2002) have been used to compare the effectiveness of proposed national assessment methods for low frequency noise limits. The noise examples are shown in Table 12.

No.	Name	Description	Tones, characteristics
1	Traffic	Road traffic noise from a highway	None – broadband, continuous
2	Drop forge	Isolated blows from a drop forge transmitted through the ground	None – deep, impulsive sound
3	Gas turbine	Gas motor in a CHP plant	25 Hz, continuous
4	Fast ferry	High speed ferry; pulsating tonal noise	57 Hz, pass-by
5	Steel factory	Distant noise from a steel rolling plant	62 Hz, continuous
6	Generator	Generator	75 Hz, continuous
7	Cooling	Cooling compressor	(48 Hz, 95 Hz) 98 Hz, continuous
8	Discotheque	Music, transmitted through a building	None, fluctuating, loud drums

Table 12. Comparison of test noises.

Noise no. 1 is from a busy six-lane highway and it is almost continuous. Noise no. 2 consists of a series of very deep, rumbling single blows from a drop forge. Noises 3, 4, 5, and 6 each have one tonal component. Noise no. 7 has three tones but two of them are at a low level, and noise no. 8 has a characteristic rhythmical pulsating sound. The noises were selected to represent typical low frequency noise known to cause complaints. All noises had a clear low frequency character.

The noises were presented to 18 otologically normal young listeners in two minute durations and at levels of 20 dB, 27.5 dB, and 35 dB L_{Aeq} , in simulated indoor conditions. A special group of four older people (41 – 57 years old), who were known to be disturbed by low frequency noise, were also tested with the same noises. The subjects made annoyance judgements depending on assumed circumstances, such as day, evening and night. For example, Table 13 gives the night annoyance for the main group on a numerical scale, where 0 is not annoying and 10 is very annoying.

Nominal presentation level	20 dB	27.5 dB	35 dB
Noise example	Subjective annoyance Night	Subjective annoyance Night	Subjective annoyance Night
Traffic noise	1.6	3.4	5.2
Drop forge	4.3	5.9	6.9
Gas turbine	0.9	2.5	5.2
Fast ferry	0.9	3.2	5.4
Steel factory	1.0	2.7	4.9
Generator	1.7	3.2	5.0
Cooling compressor	2.7	4.4	6.0
Discotheque	3.0	5.4	6.7

Table 13. Subjective assessment of the annoyance, main group - if the noise was heard at night.

The special group were more annoyed by the noise as shown in Table 14.

Nominal presentation level	20 dB	27.5 dB	35 dB
Noise example	Subjective annoyance Night	Subjective annoyance Night	Subjective annoyance Night
Traffic noise	4.7	7.2	8.5
Drop forge	7.5	8.3	8.9
Gas turbine	5.0	8.1	9.8
Fast ferry	6.6	8.8	9.3
Steel factory	5.8	8.2	9.3
Generator	8.4	8.3	9.0
Cooling compressor	7.4	8.5	9.1
Discotheque	6.0	7.9	8.6

Table 14. Subjective assessment of the annoyance, sensitive group - if the noise was heard at night.

The special group judged noises differently from the main group, as shown in Table 15. Here it is seen that the special group found all noises more annoying than the main group did, but that they were most annoyed by the type of noises they complained about, perhaps indicating conditioning.

Ref Group order	Average scaling	Special group order	Average scaling
Drop forge	5.1	Generator	7.3
Discotheque	4.6	Cooling compressor	7.2
Cooling compressor	4.1	Drop forge	7.0
Generator	3.1	Gas turbine	6.9
Traffic noise	3.0	Fast ferry	6.9
Fast ferry	2.9	Steel factory	6.8
Steel factory	2.7	Discotheque	6.2
Gas turbine	2.7	Traffic noise	5.6
Average	**3.5**	**Average**	**6.7**

Table 15. Comparison of group noise ordering.

These subjective evaluations were then compared with the objective methods in the National procedures as shown in Table 16. It is seen that the Danish method gives best correlation with subjective evaluation, but this depends on the 5dB penalty for impulsive sounds. Without this penalty, it is similar to the German and Swedish methods.

Assessment method	Correlation coefficient, ρ
Danish	0.94
German non-tonal	0.73
German tonal	0.72
Swedish	0.76
Polish	0.71
Dutch proposal	0.64
C-level	0.66

Table 16 . Overview of the results from regression analysis of the relation between the subjective evaluations and the different objective assessment methods.

For the noises used, which are typical of low frequency noises, the infringement of the criterion curves is by a single frequency band. Only the band where the maximum excess occurs is taken into account and the excess at other frequency bands is neglected. It is seen from the comparison of the criteria in Table 11 that the curves diverge above about 40Hz, with the result that, at 100Hz, the German limit is about 15dB below the Swedish and Danish limits. Thus the different criteria will give different outcomes if the infringement is at frequencies above 40Hz.

17. Further Research

The preceding sections have shown that there are a number of gaps in our knowledge of low frequency noise. We do know that problems arise fairly widely, and on an international scale. A great deal of distress is caused to a limited number of people, who are unfortunate to be classified as "sufferers", although suffering is an apt description of the effects on them. It is no longer necessary to "make a case" for work on low frequency noise, but the direction of the work should be chosen to maximise benefit to the sufferers. There are two main areas to be addressed:

- *Assessment of the noise*
- *Development of personal coping strategies.*

Assessment assumes that there is a measurable noise.

Enhanced coping strategies are required:

- *During the time delay between occurrence of a noise and its control*
- *If the noise cannot be located.*
- *If the noise cannot be measured*

17.1 **Assessment.** A not uncommon occurrence is that there is clearly a low frequency noise present at a complaint location, but existing UK assessment methods are not able to determine its nuisance value, leading to the conclusion of "Not a Statutory Nuisance". Section 15 has outlined the assessment methods of other countries, which are able to draw positive conclusions on noises that would fail an A-weighting test. Further work should be carried out on assessment of low frequency noises, building on what is already known.

17.1.1 **Noises.** A number of noises, which are known to be causing low frequency problems, could be analysed and assessed by existing low frequency noise assessment methods. Calibrated tape recordings would be made of the noises, so that time variations could be evaluated. An attempt would also be made to determine an "annoyance rating" for the complainant. This would be through questioning and discussion in order to evaluate both the level of annoyance and the personality of the complainant.

The interdependence of spectra, fluctuations and complainant characteristics would be used to develop an assessment method that is more reliable than existing methods.

17.1.2 **Benefits.** The work would provide a means of assessing low frequency noises, for piloting by Environmental Health Officers and ultimately included in national recommendations.

17.2 **Coping strategies.** Some Hum sufferers report that they have been able to adopt strategies which ease the effects on them of their noise of unknown origin. In a few cases a complete "cure" has been achieved. An element of the strategy is to stop fighting the noise and relax one's physical and mental responses to it. There is a great deal to be learned from the methods of tinnitus management, which have developed over the past 20 years. This is not to imply that those low frequency noises which cannot be sourced are actually tinnitus, but that the experiences are similar; the complainant hears a noise that elicits a negative reaction. The research on coping strategies could evolve in the following way:

- *Consult with former sufferers who have accommodated to their noise, in order to learn from their strategies*
- *In parallel with this consult with tinnitus management specialists on their techniques.*
- *Recommend strategies for management of low frequency noise problems.*
- *Carry out field studies of management of low frequency noise. Where necessary co-operate with social services and GP.*
- *Follow up later to assess the results.*
- *Develop a training programme for EHO's and personal advice for sufferers.*

17.2.2 **Benefits.** The work has the potential to improve the quality of life of complainants, reduce the level of complaints of noise and also reduce the demands on environmental, social and health services. It will reduce the extent to which low frequency noise complaints become stuck in the system, as many do at present, with costly and damaging results.

References [1]

ACGIH (2001): Documentation on the threshold limit values for physical agents. *7th Edition*.

Adam, R. (1999): Subjective response to low frequency noise, PhD, South Bank University, London.

Alekseev, S. V., Glinchikov, V. V., and Usenko, V. R. (1985): Myocardial ischemia in rats exposed to infrasound. *Gig Tru Prof Zabol*, 34 - 38.

Alekseev, S. V., Glinchikov, V. V., and Usenko, V. R. (1987): Reaction of the liver cells to infrasound. *Noise and Vibration Bulletin*, 131 - 132.

Andresen, J., and Møller, H. (1984): Equal annoyance contours for low frequency noise. *Jnl Low Freq Noise Vibn* **3**, 1-9.

Backteman, O., Köhler, J., and Sjöberg, L. (1983a): Infrasound - Tutorial and review. Part 1. *Jnl Low Freq Noise Vibn* **2**, 1-31.

Backteman, O., Köhler, J., and Sjöberg, L. (1983b): Infrasound -Tutorial and review. Part 2. *Jnl Low Freq Noise Vibn* **2**, 176-210.

Backteman, O., Köhler, J., and Sjöberg, L. (1984a): Infrasound. Tutorial and review. Part 3. *Jnl Low Freq Noise Vibn* **3**, 28-67.

Backteman, O., Köhler, J., and Sjöberg, L. (1984b): Infrasound- Tutorial and review. Part 4. *Jnl Low Freq Noise Vibn* **3**, 96-113.

Barbenza, C. M., Bryan, M. E., and Tempest, W. (1970): Individual loudness functions. *J Sound Vibration* **11**, 399-410.

Baron-Cohen, S. (1996): Is there a normal phase of synaesthesia in development. See Volume 2 of. *http://psyche.csse.monash.edu.au/*

Baron-Cohen, S., and Harrison, J. E. (1997): *Synaesthesia*. Blackwell.

Belojevic, G., and Jokovljevic, B. (2001): Factors influencing subjective noise sensitivity in an urban population. *Noise and Health* **4**, 17-24.

Benton, S. (1984): An investigation into the effects of low level low frequency noise on individual behaviour, Ph D Chelsea College, London University.

Benton, S. (1997a): Measurement challenges in assessing the annoying characteristics of noise. Is low frequency noise a special case. *Jnl Low Freq Noise Vibn* **16**, 13-24.

Benton, S. (1997b): Low frequency noise and the impact upon an individuals quality of life: Case study reports. *Jnl Low Freq Noise Vibn* **16**, 203-208.

Benton, S., and Leventhall, H. G. (1982): The effect of auditory processing on the development of low level low frequency noise criteria. *Jnl Low Freq Noise Vibn* **1**, 97-108.

Benton, S., and Leventhall, H. G. (1994): The role of "background stressors" in the formation of annoyance and stress responses. *Jnl Low Freq Noise Vibn* **13**, 95-102.

Benton, S., and Yehuda-Abramson, O. (2002): Low frequency noise annoyance. Results of a UK survey into the incidence and intervention methods reported by Environmental Health Officers. Proc. 10th International Meeting Low Frequency Noise and VIbration and its Control. York UK (Editor: H G Leventhall), 55-60.

Beranek, L. L., Blazier, W. E., and Figwer, J. J. (1971): Preferred Noise Criterion Curves (PNC) and their application to rooms. *J Acoust Soc Am* **50**, 1223-1228.

[1] The internet links given as references were last checked on 20 March 2003

Berglund, B., Hassmen, P., and Job, R. F. (1996): Sources and effects of low frequency noise. *J Acoust Soc Am* **99**, 2985-3002.
Berglund, B., Lindvall, T., Schwela, D., and Goh, K.-T. (2000): Guidelines for Community Noise. *World Health Organisation*.
Blazier, W. E. (1981): Revised noise criteria for application in the acoustic design of and rating of HVAC systems. *Noise Control Eng* **16**, 64-73.
Blazier, W. E. (1997): RC Mark II: A refined procedure for rating noise of heating ventilating and air conditioning (HVAC) systems in buildings. *Noise Control Eng* **45**, 243-250.
Bohne, B. A., and Harding, G. W. (2000): Degeneration in the cochlea after noise damage. Primary versus secondary events. *Amer J Otology* **21**, 505 - 509.
Borredon, P. (1972): Reaction Physiologiques des subjets humain exposes a des infrason. *Report 3713 Centre des Recherche de Medicin Aeronautique*.
Bradley, J. S. (1994): Annouyance caused by constant amplitude and amplitude modulated sounds containing rumble. *Noise Control Eng* **42**, 203-208.
Broner, N. (1978a): The effects of low frequency noise on people: A review. *J Sound Vibration* **58**, 483-500.
Broner, N. (1979): Low frequency noise annoyance. *PhD Chelsea College, University of London*.
Broner, N., and Leventhall, H. G. (1978b): Individual annoyance functions. *Acoustics Letters* **2**, 22-25.
Broner, N., and Leventhall, H. G. (1983): Low frequency noise annoyance assessment by Low Frequency Noise Rating (LFNR) Curves. *Jnl Low Freq Noise Vibn* **2**, 20-28.
Broner, N., and Leventhall, H. G. (1984): The annoyance, loudness and unacceptability of lower level low frequency noise. *Jnl Low Freq Noise Vibn* **3**, 154-166.
Broner, N., and Leventhall, H. G. (1985): Annoyance and unacceptability of higher level low frequency noise. *Jnl Low Freq Noise Vibn* **4**, 1-11.
Brown, F. D. (1976): Acoustically induced chest vibrations. *MSc Chelsea College, University of London*.
Bryan, M. E. (1976): Low frequency noise annoyance. In: Infrasound and Low Frequency Vibration. Editor: W Tempest. Academic Press.
Bryan, M. E., and Tempest, W. (1973): Are our noise laws adequate. *Applied Acoustics* **6**, 219-233.
Burdick, C. K., Patterson, J. H., Mozo, B. T., and Camp, R. T. (1978): High frequency hearing loss incurred by exposure to low frequency noise.
Casella-Stanger (2002): Report : Low Frequency Noise : Technical Research Support for DEFRA Noise Programme, Department for the Environment, Food and Rural Affairs, London.
Challis, L. A., and Challis, A. M. (1978): Low frequency noise problems from gas turbine power stations. Proc Internoise 78, pp. 475-480.
Cheyne, J. A., Newby-Clark, I. R., and Reuffer, S. D. (1999): Relations among hypnagogic and hypnopompic experiences associated with sleep paralysis. *J Sleep Res* **8**, 313-317.
Cocchi, A., Fausti, P., and Piva, S. (1992): Experimental characteristics of the low frequency noise annoyance arising from industrial plants. *Jnl Low Freq Noise Vibn* **11**, 124-132.
Cohen, M. F. (1982): Detection threshold microstructure and its effect on temporal integration data. *J Acoust Soc Am* **71**, 405-409.
Corso, J. F. (1958): Absolute thresholds for tones of low frequency. *Am. J Psych* **71**, 367-374.

Danielsson, A., and Landstrom, U. (1985): Blood pressure changes in man during infrasonic exposure. An experimental study. *Acta Med Scand* **217**, 531 - 535.
Dawson, H. (1982): Practical aspects of the low frequency noise problem. *Jnl Low Freq Noise Vibn* **1**, 28-44.
DIN:4560 (1997): Measurement and evaluation of low-frequency environmental noise.
DIN:45680 (1997): Measurement and evaluation of low-frequency environmental noise.
Elder, J. A., and Chou, C. K. (2003 (submitted for publication)): Human auditory perception of pulsed radiofrequency energy. *Bioelectromagnetics*.
Evans, M. J., and Tempest, W. (1972): Some effects of infrasonic noise in transportation. *J Sound Vibration* **22**, 19-24.
Fecci, R., Barthelemy, R., Bourgoin, J., Mathias, A., Eberle, H., Moutel, A., and Jullien, G. (1971): Effects of infrasound on the organism. *La Medecina del Lavaro* **62**.
Fields, J. M. (1993): Effect of personal and situational variables on noise annoyance in residential areas. *J Acoust Soc Am* **93**, 2753-2763.
Fields, J. M. (2001): An updated catalog of 521 social surveys of resident's reaction to environmental noise. *Nasa Report: NASA/CR-2001-211257*.
Firstenberg, A. (2001): Radio Wave Packet www.goodhealthinfo.net/radiation/radio_wave_packet.pdf
Frey, A. H. (1962): Human auditory system response to modulated electromagnetic energy. *J Appl Physiol.* **17**, 689-692.
Frost, G. P. (1980): An investigation into the microstructure of the auditory threshold between 1kHz and 2kHz MSc: *Chelsea College*, London University.
Frost, G. P. (1987): An investigation into the microstructure of the low frequency auditory threshold and of the loudness function in the near threshold region. *Jnl Low Freq Noise Vibn* **6**, 34-39.
Goldstein, M. (1994): *Low-frequency components in complex noise and their perceived loudness and annoyance*. National Institute of Occupational Health (Arbetsmiljöinstitutet). Solna.
Goldstein, M., and Kjellberg, A. (1985): Annoyance and low frequency noise with different slopes of the frequency spectrum. *Jnl Low Freq Noise Vibn* **4**, 43-51.
Gordeladze, A. S., Glinchikov, V., and Usenko, V. R. (1986): Experimental myocardial ischemia caused by infrasound. *Gig Tru Prof Zabol*, 30 -33.
Green, J. E., and Dunn, F. (1968): Correlation of naturally occurring infrasonics and selected human behavior. *J Acoust Soc Am* **44**, 1456-1457.
Grime, S. (2000): Against a National Noise Strategy. *Environmetal Health Journal* **108**.
Grossenbacher, P. G. (1997): Perception and sensory information in synaesthetic experience. *in Baron-Cohen S and Harrison J E (1997)*.
Guest, H. (2002): Inadequate standards currently applied by local authorities to determine statutory nuisance from LF and infrasound. 10th International Meeting Low Frequency Noise and VIbration and its Control. York UK (Editor: H G Leventhall), 61-68.
Guski (1999): Personal and social variables as codeterminants of noise annoyance. *Noise and Health* **1**, 45-56.
Guski, R., Felscher-Suhr, U., and Scheumer, R. (1999): The concept of noise annoyance: How international experts see it. *J Sound Vibration* **223**, 513-527.
Harris, C. S. (1976): Review of the effects of infrasound on man. *Aviat Space Environ Med* **47**, 430-434.
Harris, C. S., and Johnson, D. L. (1978): Effects of infrasound on cognitive performance. *Aviat Space Environ Med* **49**, 582-6.
Harris, C. S., Sommer, H. C., and Johnson, D. L. (1976): Review of the effects of infrasound on man. *Aviat Space Environ Med* **47**, 582-6.

Hatfield, J., Job, R., Carter, N., Peploe, P., Taylor, R., and Morrell, S. (2001): The influence of psychological factors on self-reported physiological effects of noise. *Noise and Health* **3**, 1-13.
Holmberg, K., Landstrom, U., and Kjellberg, A. (1997): Low frequency noise level variations and annoyance in working environments. *Jnl Low Freq Noise Vibn* **16**, 81-88.
Holmberg, K., Landström, U., and Kjellberg, A. (1993): Effects of ventilation noise due to frequency characterisitics and sound level. *Jnl Low Freq Noise Vibn* **12**, 115-122.
Holmberg, K., Landström, U., Söderberg, L., and Kjellberg, A. (1996): Hygienic assessment of low frequency noise annoyance in working environments. *Jnl Low Freq Noise Vibn* **15**, 7-16.
Hood, R. A., and Leventhall, H. G. (1971): Field measurement of infrasonic noise. *Acustica* **25**, 10-13.
IEC:60651 (2001): Sound level meters.
Inaba, R., and Okada, A. (1988): Study of the effect of infra- and low frequency sound on sleep by EEG recording. *Jnl Low Freq Noise Vibn* **7**, 15-19.
Inukai, Y., Nakamura, N., and Taya, H. (2000): Unpleasantness and acceptable limits of low frequency sound. *Jnl Low Freq Noise Vibn* **19**.
Inukai, Y., Taua, H., Utsugi, A., and Nagamur, N. (1990): A new evaluation method for low frequency noise. *Proc Internoise 90*, 1441.
Ising, H., and Ising, M. (2002): Chronic cortisol increases in the first half of the night caused by road traffic noise. *Noise and Health* **4**, 13-21.
ISO226 (1987): Normal equal-loudness level contours.
ISO389-7 (1996): Reference zero for calibration of audiometric equipment. Part 7: Reference threshold of hearing under free field and diffuse field listening.
ISO532 (1975): Method for calculating loudness level.
ISO7196 (1995): Frequency weighting characteristics for infrasound measurements.
ISO 398 - 7 (1996): Reference zero for calibration of audiometric equipment - Part 7 Reference threshold of hearing under freee-field and diffuse-field listening conditions.
Jakobsen, J. (2001): Danish guidlines on environmental low frequency noise, infrasound and vibration. *Jnl Low Freq Noise Vibn & Active Control* **20**, 141-148.
Jerger, J., Alford, B., Coats, A., and French, B. (1966): Effects of very low frequency tones on auditory thresholds. *J Speech and Hearing Research* **9**, 150-160.
Johnson, D. L. (1975): Auditory and physiological effects of infrasound. *Proc Internoise 75, Sendai*, 475 - 482.
Johnson, D. L. (1982): Hearing hazards associated with infrasound. In:. *New perspectives in noise induced hearing loss. Eds. Hamernik, RP, Henderson, SR. Raven Press New York*, 407-421.
Jones, L. (undated): Human factors and haptic interfaces. *www.ima.umn.edu/talks/workshops/6-14-15.2001/jones/jones/.pdf*
Kalveram, K. T. (2000): How acoustical noise can cause physiological and psychological reactions. 5th Int Symp Transport Noise and Vibration. June 2000, St. Petersburg, Russia.
Kalveram, K. T., Dasow, J., and Vogt, J. (1999): How information about the source influences noise annoyance. ASA/EAA/DAGA Meeting March 1999, Berlin (CDROM).
Karpova, N. I., Alekseev, S. V., Erohkin, V., Kayskina, E. N., and Reutov, R. P. (1970): Early response of the organism to low frequency acoustic oscillations. *Noise and Vibration Bulletin* **11**, 100-103.

Kawano, A., Yamaguchi, H., and Funasaka, S. (1991): Effects of infrasound on humans: A questionnaire survey of 145 drivers of long distance transport trucks. *Pract Otol Kyoto* **84**, 1325 - 1324.

Kellaris, J. (2001): Identifying properies of tunes that get "stuck in your head": Toward a theory of cognitive itch. *Proc: Winter Conference 2001 Society for Consumer Psychology. S E Heckler and S Shapiro Eds.*

Kitamura, T., and Yamada, S. (2002): Psychological analysis of sufferers of low frequency noise and relation between brain structure and psychological response. *Proc 10th International Meeting Low Frequency Noise and Vibration and its Control. York, UK Sept 2002(Editor: H G Leventhall)*.

Kjellberg, A., and Goldstein, M. (1985): Loudness assessment of band noise of varying bandwidth and spectral shape. An evaluation of various frequency weighting networks. *Jnl Low Freq Noise Vibn* **4**, 12-26.

Kjellberg, A., Goldstein, M., and Gamberale, F. (1984): An assessment of dB(A) for predicting loudness and annoyance of noise containing low frequency components. *Jnl Low Freq Noise Vibn* **3**, 10-16.

Kjellberg, A., Tesarz, M., Holberg, K., and Landström, U. (1997): Evaluation of frequency-weighted sound level measurements for prediction of low-frequency noise annoyance. *Environment International* **23**, 519-527.

Kosten, C. W., and van Os, G. J. (1962): Community reaction criteria for external noises. *NPL Symposium 12: The Control of Noise. London HMSO*.

Kraemer, S. D. (1973): Annoyance of low frequency sounds. *MSc Chelsea College, University of London*.

Krylov, V. V. (1995): Generation of low frequency ground vibrations by sound waves propagating in underground gas pipes. *Jnl Low Freq Noise Vibn* **14**, 143-150.

Krylov, V. V. (1997): Investigation of environmental low frequency noise. *Applied Acoustics* **51**, 33-51.

Kyriakides, K. (1974): A sudy of environmental infrasound and some effects of infrasound on task performance.

Kyriakides, K., and Leventhall, H. G. (1977): Some effects of infrasound on task performance. *J Sound Vibration* **50**, 369-388.

Landström, U. (1987): Laboratory and field studies on infrasound and its effects on humans. *Jnl Low Freq Noise Vibn* **6**, 29-33.

Landström, U., and Byström, M. (1984): Infrasonic threshold levels of physiological effects effects. *Jnl Low Freq Noise Vibn* **3**, 167-173.

Landström, U., Byström, M., and B, N. (1985): Changes in wakefulness during exposure to noise at 42Hz, 1000Hz and individual EEG frequencies. *Jnl Low Freq Noise Vibn* **4**, 27-33.

Landström, U., Kjellberg, A., and Byström, M. (1993): Acceptable levels of sounds with different spectral characteristics during the performance of a simple and a complex non-auditory task. *J Sound Vibration* **160**, 533-542.

Landström, U., Kjellberg, A., Söderberg, L., and Nordström, B. (1994): Measures against ventilation noise: Which tone frequencies are least and most annoying. *Jnl Low Freq Noise Vibn* **13**, 81-88.

Landström, U., Kjellberg, A., Söderberg, L., and Norström, B. (1991): The effects of broadband, tonal and masked ventilation noise on performance, wakefulness and annoyance. *Jnl Low Freq Noise Vibn* **10**.

Landström, U., Liszka, L., Danielsson, A., Lindmark, A., Lundquist, P., and Söderberg, L. (1982): Changes in wakefulnes during exposure to infrasound. *Jnl Low Freq Noise Vibn* **1**, 79-87.

Landström, U., Lundström, R., and Byström, M. (1983): Exposure to infrasound - Perception and changes in wakefulness. *Jnl Low Freq Noise Vibn* **2**, 1-11.
Landström, U., and Pelmear, P. (1993): A short review of infrasound. *Jnl Low Freq Noise Vibn* **12**, 72-74.
Leventhall, H. G. (1988): Low frequency noise in buildings. Internal and external sources. *Jnl Low Freq Noise Vibn* **7**, 74-85.
Leventhall, H. G., Brown, F. D., and Kyriakides, k. (1977): Somatic responses to low frequency noise. *Proc ICA, Madrid, 1977*.
Lidstrom, I. M. (1978): The effects of infrasound on humans. *Invest Report (Umea) 1978; 33;*, 1-42.
Lundin, A., and Ahman, M. (1998): Case report: Is low frequency noise from refrigerators in a multi-family house a cause of diffuse disorders? *Jnl Low Freq Noise Vibn* **17**, 65-70.
Lydolf, M., and Møller, H. (1997a): New measurements of the threshold of hearing and equal loudness contours at low frequencies. 8th International Meeting on Low Frequency Noise and Vibration, pp. 76-84.
Lydolf, M., and Møller, H. (1997b): New measurements of the threshold of hearing and equal loudness contours at low frequencies. *Proc 8th International Meeting on Low Frequency Noise and Vibration Gothenburg 1997, 76-84,*.
Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., and Frith, C. D. (2000): Navigation related structural change in the hippocampi of taxi drivers. *Proc Nat Acad Sci* **97**, 4398 - 4403.
Manley, D. M. J. P., Styles, P., and Scott, J. (2002): Perceptions of the public of low frequency noise. *Jnl Low Freq Noise Vibn* **21**, 2002.
Marsden, P. (2001): Is suicide contagious? A case study in applied memetics. *Journal of Memetics - Evolutionary models of information transmission* **5**, See: http://jom-emit.cfpm.org.2001/vol5/.
Mirowska, M. (1998): An investigation and assessment of low frequency noise in dwellings. *Jnl Low Freq Noise Vibn* **17**, 119-126.
Mirowska, M. (2001): Evaluation of low frequency noise in dwellings. New Polish recommendations. *Jnl Low Freq Noise Vibn* **20**, 67-74.
Mirowska, M., and Mroz, E. (2000): Effect of low frequency noise at low levels on human health in light of questionnaire investigation. *Proc Inter-Noise 2000, 5, 2809 - 2812*.
Mohr, G. C., Cole, J. N., Guild, E., and Gierke, H. E. v. (1965): Effects of low frequency and infrasonic noise on man. *Aerospace Medicine* **36**, 817-824.
Møller, H. (1984): Physiological and psychological effects of infrasound on humans. *Jnl Low Freq Noise Vibn* **3**, 1-17.
Møller, H. (1987): Annoyance of audible infrasound. *Jnl Low Freq Noise Vibn* **6**, 1-17.
Moller, H., and Andresen, J. (1984): Loudness of pure tones at low and infrasonic frequencies. *Jnl Low Freq Noise Vibn* **3**, 78-87.
Møller, H., and Andresen, J. (1984): Loudness of pure tones at low and infrasonic frequencies. *Jnl Low Freq Noise Vibn* **3**, 78-87.
Møller, H., and Lydolf, M. (2002): A questionnaire survey of complaints of infrssound and low frequency noise. *Jnl Low Freq Noise Vibn* **21**, 53 - 65.
Moos, W. S. (1963): Effects of "Föhn" weather on the human population in the Principality of Lichtenstein. *Aerospace Medicine* **34**, 736-739.
Moos, W. S. (1964): Effects of "Föhn" weather on accident rates in the City of Zurich (Switzerland). *Aerospace Medicine* **35**, 643-645.
N S G (1999): NSG-Richtlijn Laagfrequent Geluid.

Nakamura, N., and Inukai, Y. (1998): Proposal of models which indicate unpleasantness of low fequency noise using exploratory factor analysis and structural covariance analysis. *Jnl Low Freq Noise Vibn* **17**, 127-132.
National Institute of Environemtal Health Sciences, and National Institute of Health (Australia) (2002): EMF: Electric and magnetic fields associated with the Use of electric power. *http://www.niehs.nih.gov/emfrapid*
Nekhoroshev, A. S. (1985): Exposure to low frequeny narrow band noise and reaction of the stria vascularis vessels. *Vestn Otolaringol*, 17 - 19.
Nekhoroshev, A. S., and Glinchikov, V. V. (1991): Morphofunctional changes in the myocardium under exposure to infrasound. *Noise and Vibration Bulletin*, 56 - 58.
Nekhoroshev, A. S., and Glinchikov, V. V. (1992a): Morphological research on the liver structures of experimental animals under the action of infrasound. *Aviakosm Ekol Med* **26**, 56 - 59.
Nekhoroshev, A. S., and Glinchikov, V. V. (1992b): Effects of infrasound on change in the auditory cortex. *Gig Sanit*, 62 - 64.
Nishimura, K., Kudoda, M., and Yoshida, Y. (1987): The pituitary adenocorticol response in rats and human subjects exposed to infrasound. *Jnl Low Freq Noise Vibn* **6**, 18 - 28.
Nixon, C. (1973): Human auditory response to intense infrasound. in Proceedings Colloquium on Infrasound, CNRS Paris, 24-27 Sept 1973, pp. 317-338.
Pantev, C., Oostenveld, R., A, E., Ross, B., Roberts, L. E., and Hoke, M. (1998): Increased auditory cortical response in musicians. *Nature* **April 23 392 (6678)**, 811-814.
Parker, D. E., von Gierke, H. E., and Reschke, M. (1968): Studies of acoustical stimulation of the vestibular system. *Aerospace Medicine* **39**, 1321 - 1325.
Persson, K., and Bjorkman, M. (1988): Annoyance due to low frequency noise and the use of the dB(A) scale. *J Sound Vibration* **127**, 491-497.
Persson, K., Björkman, M., and Rylander, R. (1985): An experimental evaluation of annoyance due to low frequency noise. *Jnl Low Freq Noise Vibn* **4**, 145-153.
Persson, K., Björkman, M., and Rylander, R. (1990): Loudness, annoyance and the dBA in evaluating low frequency sounds. *Jnl Low Freq Noise Vibn* **9**, 32-45.
Persson, K., and Rylander, R. (1988): Disturbance from low frequency noise in the environment: A survey among local environmental health authorities in Sweden. *J Sound Vibration* **121**, 339-345.
Persson-Waye, K. (1985): An experimental evaluation of annoyance due to low frequency noise. *Jnl Low Freq Noise Vibn* **4**, 145-153.
Persson-Waye, K., and Bengtsson, J. (2002): Assessments of low frequency noise complaints - a follow up 14 years later. 10th International Meeting Low Frequency Noise and VIbration and its Control. York UK (Editor: H G Leventhall), 103-110.
Persson-Waye, K., Bengtsson, J., Kjellberg, A., and Benton, S. (2001): Low frequency "noise pollution" interferes with performance. *Noise and Health* **4**, 33-49.
Persson-Waye, K., Bengtsson, J., Rylander, R., Hucklebridge, F., Evans, P., and Clow, A. (2002): Low frequency noise enhances cortisol among noise sensitive subjects during work performance. *Life Sciences* **70**, 745-758.
Persson-Waye, K., Clow, A., Edwards, S., Hucklebridge, F., and Rylander, R. (2003): Effects of nighttime low frequency noise on the cortisol response to awakening and subjective sleep quality. *Life Sciences* **72**, 863-875.
Persson-Waye, K., and Rylander, R. (2001): The prevalence of annoyance and effects after long term exposure to low frequency noise. *J Sound Vibration* **240**, 483-497.

Persson-Waye, k., Rylander, R., Benton, S., and Leventhall, H. G. (1997): Effects on performance and work quality due to low frequency ventilation noise. *J Sound Vibration* **205**, 467-474.
Piorr, D., and Wietlake, K. H. (1990): Assesment of low frequency noise in the vicinity of industrial noise sources. *Jnl Low Freq Noise Vibn* **9**, 116-119.
Poulsen, T. (2002): Laboratory determination of annoyance of low frequency noise. 10th International Meeting Low Frequency Noise and VIbration and its Control. York UK (Editor: H G Leventhall), 19-26, pp. 19-28.
Poulsen, T., and Mortensen, F. R. (2002): Laboratory evaluation of annoyance of low frequency noise. *Working Report No.1 2002 Danish Environmental Protection Agency*.
Rice, S. O. (1954): Mathematical analysis of random noise. *In: Selected papers on noise and stochastic processes (Ed: N Wax) Dover*.
Rich, A. N., and Mattingley, J. B. (2002): Anomolous perception in synaesthesia: A cognitive neuroscience perspective. *Nature Reviews - Neuroscience* **3**, 43-52.
Ross, S. E. (1999): "Memes" as infectious agents in psychosomatic illness. *Annals of Internal Medicine* **131**, 867 - 871.
Rushforth, I., Moorhouse, A., and Styles, P. (2002): A case study of low frequency noise assessed using DIN 45680 criteria. *Jnl Low Freq Noise Vibn* **21**, to be published.
Rushforth, I., Styles, P., Manley, D. M. J. P., and Toon, S. M. (1999): Microseismic investigations of low frequency vibrations and their possible effects on populations. *Jnl Low Freq Noise Vibn* **18**, 111-122.
Sargent, J. W. (1996): A study of environmental low frequency noise complaints. *Proc IoA* **17**.
Schnupp, J. W. H., and Kacelnick, O. (2002): Cortical plasticity: Learning from cortical reorganisation. *Current Biology* **12**, 144-146.
Shvaiko, I. I., Koairin, I. P., Mikhaliuk, I. A., and Motuzkov, I. N. (1984): Effect of infrasound on the metabolism of trace elements in the body. *Gig San*, 91 - 92.
Slarve, R. N., and Johnson, D. L. (1975): Human whole-body exposure to infrasound. *Aviat Space Environ Med* **46**, 428-431.
Sloven, P. (2001): A structured approach to LFS complaints in the Rotterdam region of the Netherlands. *Jnl Low Freq Noise Vibn* **20**, 75-84.
Socialstyrelsen-Sweden (1996): SOSFS 1996:7/E Indoor Noise and High Sound Levels.
Stallen, P. (1999): A theoretical framework for environmental noise annoyance. *Noise and Health* **1**, 69-80.
Stephens, R., and Bate, A. (1966): Acoustics and Vibrational Physics. *Edward Arnold (Publisher)*.
Svidovyi, V. I., and Glinchikov, V. V. (1987): Action of infrasound on the lung structure. *Noise and Vibration Bulletin*, 153 - 154.
Svidovyi, V. I., and Kuklina, O. I. (1985): State of the hemolymph circulatory bed of the conjunctive as affected by infrasound. *Gig Tru Prof Zabol*, 51 - 52.
Taenaka, K. (1989): A study on the effect of infrasound. *J Oto Rhino Laryngol Soc Jpn* **92**, 1399 - 1415.
Tagikawa, H., Hayashi, F., Sugiura, S., and Sakamoto, H. (1988): Effects of infrasound on human body sway. *Jnl Low Freq Noise Vibn* **7**, 66-73.
Takahashi, Y., Kanada, K., and Yoshiharu, Y. (2002): Some characteristics of human body surface vibration induced by low frequency noise. *Jnl Low Freq Noise Vibn* **21**, 9-20.

Takahashi, Y., and Maeda, S. (2002): Measurement of human body surface vibration induced by complex low frequency noise. 10th International Meeting Low Frequency Noise and VIbration and its Control. York UK (Editor: H G Leventhall), 135-142.
Tempest, W. (1989): A survey of low frequency noise complaints received by local authorities in the United Kingdom. *Jnl Low Freq Noise Vibn* **8**, 45-49.
Tesarz, M., Kjellberg, A., Landström, U., and Holmberg, K. (1997): Subjective response patterns related to low frequency noise. *Jnl Low Freq Noise Vibn* **16**, 145-150.
Tierney Jr, L. M., McPhee, S. J., and Papadatis, M. A. (2003): Current Medical Diagnosis and Treatment, 42nd Edition. *Lange Medical Books/ Mcgraw-Hill*.
van den Berg, G. P. (2001): Tinnitus as a cause of low frequency noise complaints. *Proc Internoise 2001, den Hague*.
van den Berg, G. P., and Passchier-Vermeer, W. (1999a): Assessment of low frequency noise complaints. Proc Internoise'99, Fort Lauderdale.
Vasudevan, R. N., and Gordon, C. G. (1977): Experimental study of annoyance due to low frequency environmental noise. *Applied Acoustics* **10**, 57-69.
Vasudevan, R. N., and Leventhall, H. G. (1982): A study of annoyance due to low frequency noise in the home. *Jnl Low Freq Noise Vibn* **2**, 157-164.
Vercammen, M. L. S. (1989): Setting limits for low frequency noise. *Jnl Low Freq Noise Vibn* **8**, 105-109.
Vercammen, M. L. S. (1992): Low frequency noise limits. *Jnl Low Freq Noise Vibn* **11**, 7-13.
von Gierke, H. E. (1973): Effects of infrasound on man. *Proc. Colloquium on Infrasound. CNRS, Paris, 1973*, 417 - 435.
von Gierke, H. E., and Nixon, C. (1976): Effects of intense infrasound on man. In: Infrasound and Low Frequency Vibration. Editor: W Tempest. Academic Press.
Walford, R. E. (1978): Acoustical aspects of some hum complaints DCC: *Chelsea College*, London University.
Walford, R. E. (1983): A classification of environmental "hums" and low frequency tinnitus. *Jnl Low Freq Noise Vibn* **2**, 60-84.
Watanabe, T., and Møller, H. (1990a): Hearing thresholds and equal loudness contours in free field at frequencies below 1kHz. *Jnl Low Freq Noise Vibn* **9**, 135-148.
Watanabe, T., and Møller, H. (1990b): Low frequency hearing thresholds in pressure field and free field. *Jnl Low Freq Noise Vibn* **9**, 106-115.
Westin, J. B. (1975): Infrasound: A short review of effects on man. *Aviat Space Environ Med* **46**, 1135-40.
Whittle, L. S., Collins, S. J., and Robinson, D. W. (1972): The audibility of low frequency sounds. *Jnl Sound Vibn* **21**, 431-448.
WHO (1999): Fact Sheet No. 226 Electromagnetic fields and public health. Radars and human health, www.who.int/inf-fs/en/fact226.html
Yamada, S. (1980): Hearing of low frequency sound and influence on the body. Conference on Low Frequency Noise and Hearing, Aalborg, Denmark, 95-102, (Editors: H Møller and P Rubak).
Yamada, S., Ikuji, M., Fujikata, S., Watanabe, T., and Kosaka, T. (1983): Body sensations of low frequency noise of ordinary persons and profoundly deaf personsl. *Jnl Low Freq Noise Vibn* **2**, 32-36.
Yamada, S., Watanabe, T., Kosaka, T., and Oshima, N. (1987): Construction and analysis of a data-base of low frequency noise problems. *Jnl Low Freq Noise Vibn* **6**, 114-118.

Yeowart, N. S. (1976): Thresholds of hearing and loudness for very low frequencies. In: Infrasound and Low Frequency Vibration. Editor: W Tempest. Academic Press, pp. 37-64.
Yeowart, N. S., and Evans, M. J. (1974): Thresholds of audibility for very low frequency pure tones. *J Acoust Soc Am* **55**, 814-818.