Community Noise

Edited by

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Abstract. The document critically reviews the adverse effects of community noise, including interference with communication, noise-induced hearing loss, annoyance responses, and effects on sleep, the cardiovascular and psychophysiological systems, performance, productivity, and social behavior. Noise measures or indices based only on energy summation are not enough for the characterization of most noise environments. This is particularly true when concerned with health assessment and predictions. It is equally important to measure and display the maximum values of the noise fluctuations, preferably combined with a measure of the number of noise events, and to assess whether the noise includes a large proportion of low frequency components. For dwellings, recommended guideline values inside bedrooms are 30 dB LAeq for steady-state continuous noise and for a noise event 45 dB LAmax. To protect the majority of people from being seriously annoyed during the daytime, the sound pressure level from steady, continuous noise on balconies, terraces, and in outdoor living areas should not exceed 55 dB LAeq. To protect the majority of people from being moderately annoyed during the daytime, the sound pressure level should not exceed 50 dB LAeq. At nighttime outdoors, sound pressure levels should not exceed 45 dB LAeq, so that people may sleep with bedroom windows open. In schools and preschools, to be able to hear and understand spoken messages in class rooms, the sound pressure level should not exceed 35 dB LAeq during teaching sessions. For hearing impaired children, a still lower level may be needed. The reverberation time in the class room should be about 0.6 s, and preferably lower for hearing impaired children. For assembly halls and cafeterias in school buildings, the reverberation time should be less than 1 s. For outdoor playgrounds the sound pressure level from external sources should not exceed 55 dB LAeq. In hospitals during nighttime, the recommended guideline values for wardrooms should be 30dB LAeq together with 40 dB LAmax. Since patients have less ability to cope with stress, the equivalent soundpressure level should not exceed 35

dB LAeq in most rooms in which patients are being treated, observed or resting. The concern for protecting young people's hearing during leisure time activities warrants provisional guidelines for concert halls, outdoor concerts and discotheques. It is recommended that patrons should not be exposed to sound pressure levels greater than 100 dB LAeq during a 4-hour period. The same guideline values apply for sounds played back in headphones when converted to equivalent free-field level. To avoid hearing deficits from toys and fireworks, performers and audience should not be exposed to more than 140 dB(peak) of impulsive sounds. Existing large, quiet outdoor areas in parkland and conservation areas should be preserved and the background-to-noise ratio be kept low.

Foreword

This document is prepared for the World Health Organization (WHO) and is a revision of the earlier WHO document "Noise" (WHO Environ- mental Health Criteria 12, Geneva: World Health Organization, 1980) but is expanded largely and supplemented with, i.a., sections on physiology of hearing and related mechanisms, on psychoacoustics, and on mental and behavioral effects of noise. Guidelines for levels of community noise in different environments are also included. The document does not focus on occupational industrial noise.

A draft document of "Community Noise" was prepared by Professor Birgitta Berglund, Stockholm University, and Professor Thomas Lindvall, Karolinska Institute, Stockholm, on behalf of the WHO and the Nordic Noise Group of the Nordic Council of Ministers. Published international and national reviews of community noise have been consulted during the preparation of the document and are listed in the reference list.

A Task Force composed of 18 participants from 9 countries covering three regions of the WHO and two international organizations gathered in the City of Düsseldorf, Federal Republic of Germany, from 24 to 28 November, 1992 (see List of Contributors). The scope and purpose of the meeting were to make an in-depth review of the draft document. Professor Gerd Jansen served as chairperson, Dr. Bernd Rohrmann as vice chairperson and Professor Birgitta Berglund and Professor Thomas Lindvall as rapporteurs. A report on the Task Force Meeting has been published and comprises the recommendations agreed upon (Executive Summary of the Environmental Health Criteria Document on Community Noise. Copenhagen: World Health Organization, 1993). In this document, these recommendations appear in Chapter 11, Section 1.

After the Task Force Meeting in Düsseldorf, a number of written comments were received and considered in the draft document by the two rapporteurs and Professor Xavier Bonnefoy of the WHO Regional Office for Europe. Before and after the Task Force Meeting, drafts of the document or parts of it were sent out for review among scientists all over the world, including the members of the WHO Task Force, the officers and the chair- and cochairpersons of the International Commission on Biological Effects of Noise (ICBEN), and the members of the Nordic Noise Group.

An external review draft of the document was prepared by Professors Birgitta Berglund and Thomas Lindvall as editors (June 28, 1993) and was presented for comments to all participants at the ICBEN Congress on Noise as a Public Health Problem (Noise & Man '93) held in Nice, France, July 5-9, 1993. A large number of comments were received by the editors during 1993 and 1994, including comments from members of the International Institute of Noise Control Engineering (H. von Gierke, G. Maling). In addition, specific comments have been requested from specialists when the editors felt necessary to fill in obvious gaps in the document.

The editors have tried their best to accommodate all the review comments in the text and to make decisions when conflicting comments have been received. Thus, although the document is the amalgamated result of the work of a large number of persons, the complex and extended work process makes it necessary to declare that the editors are solely responsible for the present text of the document.

Both the World Health Organization's Regional Office for Europe and Headquarters are grateful to the Nordic Council of Ministers (the Nordic Noise Group) and to the German Government who provided the necessary financial support for the Task Force Meeting 1992. The efforts of all who have helped in the preparation and finalization of the document are gratefully acknowledged.

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1 INTRODUCTION

Almost 25 % of the European population is exposed, in one way or another, to transportation noise over 65 dBA (an average energy equivalent to continuous A-weighted sound pressure level over 24 hours) (Lambert & Vallet, 1994). This figure is not the same all over Europe. In some countries more than half of the population is exposed, in others less than 10 %. When one realizes that at 65 dBA sound pressure level, sleeping becomes seriously disturbed and most people become annoyed, it is clear that community noise is a genuine environmental health problem. In four European countries (France, Germany, Great Britain and the Netherlands; see Lambert & Vallet, 1994) it would seem that road traffic noise is annoying to 20-25 % of the population and railway noise to 2-4 %. In the absence of future ambitious noise abatement policies, the noise environment risks to remain unsatisfactory or even deteriorate.

The acoustic world around us continuously stimulates the auditory system. The brain selects relevant signals from the acoustic input, but the ear and the lower auditory system are continuously receiving stimulation. This is a normal process and does not necessarily imply disturbing and harmful effects. The auditory nerve provides activating impulses to the brain, which enable us to regulate our vigilance and wakefulness necessary for optimum performance.

Problems associated with noise-induced hearing loss go back to the Middle Ages. The workers in certain professions such as blacksmithing, mining, and church bell ringing were known to become deaf after years of work. However, with industrial development, the number of workers exposed to excessive noise increased significantly as has the number of people exposed to other sources of noise such as transportation noise and loud music. In industrialized societies of today, the risk of occupational noise-induced hearing loss mostly is being met by efficient technical and other countermeasures. The occupational health authorities are now much more observant of the problem than before. In developing countries, the risk for much increased rates of occupationally acquired hearing loss have to be met by strong preventive measures in engineering and medicine. Furthermore, in most countries hearing impairment due to community noise exposure (sociacusis) has become a problem of concern (Glorig, Grings, & Summerfield, 1958; B. Berglund, U. Berglund, & Lindvall, 1984).

It has been demonstrated that community noise may have a number of direct adverse effects other than hearing damage. These include adverse effects on communication, performance, and behavior; nonauditory physiological effects; noise-induced disturbance of sleep; and community annoyance.

The indirect or secondary effects of noise are often hard to quantify and satisfactory assessment models are lacking. Often, large-scale epidemiological or social surveys would be required to assess these which involve increased risks of accidents by noise-exposed individuals, reduction in productivity at work, and related effects.

There may be some populations at greater risk for adverse effects of noise. Young children (especially during language acquisition), the blind, and the hearing impaired are examples of such populations.

2 SCOPE

We are constantly exposed to noise in our daily lives. In this document noise exposure outside the industrial work place is called ”community noise” (environmental noise). Main sources of community noise are transportation systems (road, air and rail), industries, construction and public works, and neighborhood. The main indoor sources are ventilation systems, neighbors, office machines, and home appliances. Also leisure activities, such as motor sports, speed boats, and snow scooters, represent important noise sources. Community noise includes all noise sources except noise at the industrial work place.

The scope of this document is to consolidate actual scientific knowledge on the health impacts of community noise and to provide guidance to environmental health authorities and professionals trying to protect people from the harmful effects of noise. The effects of community noise on human beings are ranging from hearing damage to the feeling of annoyance. In noise abatement policy, the effects of noise on different human activities should be taken into consideration. This means that several different guideline values are suggested. Countries are expected to develop their own national and local noise standards in accordance with the amount of noise hazards they are prepared to accept.

Although it is clear that for some levels of noise exposure harmful effects are obvious, in other cases objectivity in the demonstration of health effects is difficult. The effects depend not only on the sound pressure levels but also on the “type” or ”quality” of the noise, on the number of noise events, and on the ”image” of the noise.

Noise control is always more effective and less costly if it is designed at a very early stage of development. It is more expensive to apply noise abatement measures after the noise problem has been realized. In this document, local authorities and national governments may hopefully find guidance for noise control in various type of nonindustrial environments. However, this document does not deal directly with sound pressure levels at the point of noise emission. Thus, it does not give any recommendation for limitation of sound pressure level at the noise source, but instead in the form of guideline values for adverse total noise exposure in the environments.

3 PHYSICAL ASPECTS OF NOISE

Sound is produced by any vibrating body and is transmitted in air only as as a longitudinal wave motion. It is, therefore, a form of mechanical energy and is typically measured in energy-related units. For listeners sound is defined as acoustic energy in the frequency range from 20,000 Hz to below 20 Hz that is typical of the human auditory system. The sound output of a source constitutes its power and the intensity of sound at a point in space is defined by the rate of energy flow per unit area. Intensity is proportional to the mean square of the sound pressure and, as the range of this variable is so wide, it is usual to express its value on a logarithmic scale, in decibels (dB). Sound pressure has the unit Pascal (Pa), while sound pressure level has the unit dB.

The effects of noise depend strongly upon frequency of sound-pressure oscillation. Therefore, spectrum analysis is important in noise measurement (see further, e.g., Fahy, 1989).

The perceived magnitude of sound is defined as loudness (e.g., D.M. Green, 1976). The loudness is primarily a function of intensity, frequency and temporal parameters. Various procedures exist by which loudness may be estimated from physical measurements. The simplest methods involve the measurement of the sound pressure level through a filter or network of filters that mimics the frequency response of the auditory system (weighting circuits in sound level meters).Various calculation procedures have also been developed for predicting loudness. Loudness has the unit sone, whereas loudness level has the unit phon. There is a unique relationship between sone and phon at least for levels above 40 phon or 1 sone (ISO 131, 1979a). They are both based on physical measures and should not be confused with the loudness scales that are constructed from reports of perceptions by participants in experiments or field surveys.

3.1 Definitions of Sound and Noise

Physically, sound is produced by mechanical disturbance propagated as a wave motion in air or other media. Physical sound evokes physiological responses in the ear and auditory pathways. These responses can be described and measured using appropriate methods with, for example, physical parameters (like vibratory motion of the eardrum membrane) or with electrophysiological parameters (changes in bioelectric potentials in the sensory and neural tissues). However, not all sound waves evoke auditory-physiological responses, for example, ultrasound has a frequency too high to excite the auditory system and, thus, to evoke sound perception.

Psychologically, sound is a sensory perception originating as a mental event evoked by physiological processes in the auditory brain. Other areas of the nervous system are also known to be involved. Thus, it is merely through the perceptual analysis of sounds that the complex pattern of sound waves may be classified as “Gestalts” and labeled noise, music, speech, etc. From a physical point of view there is no difference between the concepts sound and noise, although it is an important distinction for the human listener

Noise is a class of sounds that are considered as unwanted. In some situations, but not always, noise may adversely affect the health and wellbeing of individuals or populations. Since long agreed among experts, it is not possible to define noise exclusively on the basis of physical parameters of sound. Instead, it is common practice to define noise operationally as audible acoustic energy that adversely affects, or may affect, the physiological and psychological wellbeing of people.

3.2 Characteristics of Sound and Noise

Sound waves involve a succession of compressions and refractions of an elastic medium such as air. These waves are characterized by the amplitude of sound pressure changes, their frequency, and the velocity of propagation. The speed of sound (c), the frequency (f), and the wavelength (λ) are related by the equation

$$\lambda = c/f \qquad (1)$$

A mechanical energy flux accompanies a sound wave, and the rate at which sound energy arrives at, or passes through, a unit area normal to the direction of propagation is known as the sound intensity (I). Sound intensity can be defined in any direction, often as a vector. In a free sound field, the sound intensity is related to the root mean square of the sound pressure (p), the static mass density of the medium (r), and the speed of sound in the medium (c).

$$I = \frac{p^2}{rc} \qquad (2)$$

The total sound energy emitted by a source per unit time is known as the sound power and is measured in Watts (W). Sound intensity (Eq. 2) is normally measured in Watts per square meter (W/m^2).

Sounds are described by means of time-varying sound pressure, $p(t)$. Compared to the magnitude of the atmospheric pressure, the temporal variations in sound pressure, caused by sound are extremely small. The values of sound pressure between 10^{-5} and 10^2 Pa (or Newton per square meter, N/m^2, according to Système International d’Unités, SI) are relevant for the human listener. Since the range of this variable is so wide, it is usual to express its value on a logarithmic scale in dB. Sound intensity level is defined as 10 times the logarithm (to the base 10) of the ratio of the sound intensity of a target sound to the sound intensity of another sound (or alternatively, the sound pressure level as 20 times the logarithm of the ratio of their sound pressures). Any acoustic quantity that is related to sound energy, for example, power or mean square pressure, may be expressed as a dB-value. To establish an absolute level, a reference value must be agreed. Thus, the sound pressure level (L_p) of a sound expressed in dB-values depends on the mean square sound pressure (p^2) such that

$$L_p = 10 \log_{10} [p/p_{ref}]^2 \quad (3)$$

where the reference pressure p_{ref} has an internationally agreed value of $2 \cdot 10^{-5}$ N/m^2 (often given in micropascal, 20 μPa). The corresponding standardized reference values for sound power level and sound intensity level are 10^{-12} W and 10^{-12} W/m^2, respectively. Unless otherwise stated in

Table 1. How to combine two sound pressure levels expressed in dB.

Excess of Stronger Component	Add to the Stronger to Get Combined Level
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4

this document, sound pressure levels are expressed in the unit dB relative to the international standard reference quantities (i.e., dB re 20 μPa).

Whereas sound intensities or energies are additive, sound pressure levels have first to be expressed as mean square pressures, then added, and then transferred to a sound-pressure-level value again. However, this assumes uncorrelated sources. The summation of sound pressure levels can be performed by using the equation:

$$L_p = 10 \log_{10} [10^{L_{p1}/10dB} + 10^{L_{p2}/10dB} + 10^{L_{p3}/10dB} + ...] \quad (4)$$

A simple example will illustrate the use of this equation. If two sound sources of 80 dB in sound pressure level are combined, then the sound pressure level of the resulting sound will become 83 dB:

$$L = 10 \log_{10} [10^8 + 10^8] = 10 \log_{10} [2 \cdot 10^8]$$

$= 10 [\log_{10} 2 + \log_{10} 10^8] = 10 [0.3 + 8] = 83$

It is only when two sources generate similar levels that the combined output will result in a significant increase in level above the louder noise. The example just quoted gave a 3-dB increase. If there is any difference in the original, uncorrelated levels, the combined level will exceed the higher of the two levels but by less than 3 dB. When the difference between the two original levels always exceeds 10 dB, the contribution of the softer source to the combined sound pressure level may be viewed as negligible. The results of such combinations of decibel values may be found in a simplified manner by using Table 1.

Sound is measured with the aid of a microphone that generates a voltage proportional to the acoustic pressure acting upon it. This signal can be measured and analyzed using conventional electronic instrumentation. A sound level meter is usually a portable, self-contained instrument incorporating a microphone. The microphone should be calibrated so that sound pressure levels may be determined in accordance with reference pressure. If certain prerequisites are known (e.g., sound field) intensity levels and power levels can be derived from sound pressure level measurements.

The sound at a given location can be completely described in terms of the history of the sound pressure fluctuation. If this fluctuation is periodic, its fundamental frequency is the number of repetitions per second, expressed in Hertz (Hz). Most real periodic cycles are quite complex and consist of a component at the fundamental frequency and components at multiples of this base frequency, known as harmonics.

The simplest kind of sound, known as a pure tone, has a sinusoidal pressure cycle that is completely defined in terms of a single frequency and pressure amplitude at a given time. A more precise definition would also include phase which effectively defines the starting point in time, but this is usually of little or no interest.

Pure tones are relatively rare, perhaps the nearest approximation is the sound of a tuning fork. Most musical sounds are periodic but contain many harmonics. Analytically these may be expressed as a sum of harmonically related components. The frequency spectrum of a sound is not restricted to harmonic frequencies; it is discrete for periodic signals and continuous for nonperiodic signals. For examle, the frequency spectrum may specify how the energy in the periodic sound is concentrated at certain discrete frequencies. The frequency distribution of sound energy is measured by electronic filters or with the aid of a computer by calculation.

Although some kinds of machinery produce sound that is largely periodic, much sound perceived as noise is nonperiodic, that is, the sound pressure does not oscillate with time in any regular or predictable way. Such sound is said to be random. Examples of random sound include the roar of a jet engine, the rumble of distant traffic, and the hiss of escaping steam. The energy of random sound is distributed continuously over a range of frequencies instead of being concentrated at discrete values, so that its frequency spectrum may be depicted as a curve of energy density plotted against frequency.

Frequency is related, but not identical, to the perception named pitch. Any periodic sound has a tonal character that can be ascribed a particular musical note. The note is basically defined by the fundamental frequency of the sound (e.g., Small, 1970). For example, the note A above middle C on the piano has a fundamental frequency of 440 Hz. On the other hand, random sound has no distinct pitch, being characterized as a nondescript rumbling, rushing, or hissing noise, or as low and high frequency noises depending upon the range and proportion of frequencies present.

Human hearing is sensitive to frequencies in the range from about 20,000 Hz to below 20 Hz (the "audiofrequency range"). Downwards there is no established limit; frequencies down to at least 2 Hz can be detected by the ear (B. Berglund, Hassmén, & Job, 1994). Sound components lower than 16 Hz are named infrasound and those higher than 20,000 Hz ultrasound. The human hearing has a very "narrow" range of sensibility at infrasound frequencies. Whereas the sensibility range within the audiofrequency range is 120 to 140 dB, the sensibility from barely perceptable to pain is 30 to 40 dB at infrasound frequencies.

The audible frequency range is technically covered by 10 octave bands. An octave is the frequency interval the upper limit of which is twice the lower limit. The so-called "preferred frequencies" at the centers of the standardized octave bands are spaced at octave intervals from 16 to 16,000 Hz (ISO 266, 1975a). The octave band level at a particular center frequency is the level of the sound measured when all acoustic energy outside this band is excluded. One-third octave band filters, widely used for noise assessment purposes, subdivide each octave interval into three parts and provide a more detailed description of the sound spectrum.

In order to measure sound pressure level, the mean square pressure must be averaged over a certain period of time (time window). For steady-state sounds, the choice of averaging time is immaterial provided that it is long enough compared with the time period of sound pressure fluctuations. Standard sound level meters normally incorporate "fast" and "slow" response settings corresponding to averaging times of 125 ms and 1 s, respectively (IEC 651, 1979; Brüel, 1977).

Impulsive noise consists of one or more bursts of sound energy, each of a duration of less than about 1 s (ISO 2204, 1979b). Sources of impulsive noise include impacts of all kinds, for example, hammer blows, explosions, and sonic booms. These may be heard as single events or, as in the case of a stamping press, repetitively. The averaging time of the inner ear is very short (about 30 ms). To characterize impulsive sounds acoustically, it is necessary to estimate the peak sound pressures together with the duration, rise time, repetition rate, and the number of pulses. The mean square pressure of such sounds may change so rapidly that it cannot be measured with a conventional sound level meter, even using the "fast" (0.125 s) setting. For somewhat more accurate measurements, a shorter averaging time is specified for standard "impulse" sound level meters (an averaging time of 35 ms when the level is rising and of 1500 ms when it is decreasing; IEC 651, 1979). The peak level ("peak") is the level of the instantaneous peak and it is much higher than the "impulse" level.

3.3 Sound Pressure Levels and their Measurement

3.3.1 Loudness and Loudness Level

The physical magnitude of a sound is given by its intensity. The subjective or perceived magnitude is called its loudness. Primarily, loudness depends on intensity, frequency and duration (see, e.g., H. Fletcher & Munson, 1933; S.S. Stevens, 1955; Zwislocki, 1960, 1969). Binaural sound is perceived to be twice as loud as monaural sound (H. Fletcher & Munson, 1933; Hellman & Zwislocki, 1963); everyday sound exposure is typically binaural. That is one reason why knowledge from laboratory experiments may not always be generalizable to environmental conditions. Owing to the complexity of operation of the human auditory sys-

Figure. 1. Normal equal-loudness contours for pure tones (From: ISO 226, 1987a; D.W. Robinson & Dadson, 1956).

tem, it is not possible to design an objective sound measuring apparatus for all types of noise to give results which are fully comparable with those obtained by subjective methods (IEC 651, 1979).

The basic unit of loudness is the sone which is defined as the loudness of a 1,000 Hz pure tone heard at a sound pressure level of 40 dB re. 20 µPa under specified listening conditions (ISO 131, 1979a). Two sone equal twice the loudness of one sone and so on. For sound at a particular frequency, at least over a significant fraction of the practical intensity range, loudness is proportional to some power of the sound intensity. This is the psychophysical “power law” of loudness, often referred to as Stevens’s law, which is in general in accordance with the Weber fraction for just noticeable differences (S.S. Stevens, 1957b; S.S. Stevens, 1961a). In the mid audiofrequency range, the exponent of the power function is such that a twofold change in loudness corresponds to a tenfold change in intensity, that is, a 10 dB change in sound pressure level (S.S. Stevens, 1957a).

At low frequencies, loudness changes more rapidly with changes in sound pressure level. This is demonstrated in Fig. 1, which shows a standard set of equal sound pressure level contours for pure tones (D.W. Robinson & Dadson, 1956; ISO 226, 1987a). Each line shows how the sound pressure level of the tone must be varied to maintain a constant loudness (cf. the equal-loudness contours by H. Fletcher & Munson, 1933, 1957, 1958). Each iso-phon curve, in fact, represents a particular loudness level expressed in the unit phon. In other words, any tone that is perceived equally loud to a 1,000-Hz tone assumes the same phon-value as the 1,000-Hz tone. At 1,000 Hz, the phon value is identical to the dB-value. Thus, loudness level is expressed as a 1,000-Hz loudness equivalent in sound pressure level and determined under specified listening conditions (ISO 131, 1979a). For practical purposes (ISO 131, 1979a), the relationship between the scales of loudness (S, in sone) and loudness level (P, in phon) may be expressed as follows, for loudness level larger than 40 phon:

$$S = 2^{(P-40)/10} \qquad (5)$$

This equation shows that (perceived) loudness doubles for an increase of 10 phon. It also reflects the definition of sone which states that the (perceived) loudness of a 1000-Hz tone at 40 phon is 1 sone.

3.3.2 Calculation and Measurement of Loudness Level

Ideally, meters for sound pressure measurements should give a reading equal to loudness in phon. This objective is difficult to achieve, because the intervening human perceptual processes are complex. Nevertheless, such procedures have been developed and adopted as international standards (ISO

532, 1975b). Until recently they have been too complex to be incorporated into a simple measuring instrument, and, therefore, they are rarely used in practice. Presently, these techniques are being implemented in modern digital equipment.

For most practical purposes, a much simpler approach is used. The A-weighting curve is used to weight sound pressure levels as a function of frequency, approximately in accordance with the frequency response characteristics of the human auditory system for pure tones. That is, energy at low and high frequencies is de-emphasized in relation to energy in the mid-frequency range. Most precision sound level meters incorporate three selectable weighting circuits, the A-, B-, and C-weightings (IEC 651, 1979) and sometimes a D-filter (IEC 537, 1976). The characteristics of these weighting curves are illustrated in Fig. 2. The A-, B- and C-filters were intended to match the auditory-system response curves at low, moderate, and high loudness levels, respectively. Sound pressure levels in the weighted scales are measured in decibel units and are often expressed by indicating which weighting was used, for example, dBA.

The D-weighting curve is based on the so-called 40-noy curve according to Karl Kryter and is described in the now withdrawn IEC 537 (1976) "Frequency weighting for the measurement of aircraft noise". Whereas the equal-loudness contours were established for pure tones, equal-noisiness contours were based on noise bands. The unit of measurement here is noy. The rationale for constructing the equal-noisiness contours was that higher frequencies tended to be more annoying than lower frequencies although they were equally loud (Kryter, 1959, 1970, 1985, 1994). However, also the lower frequencies at the other end of the audiofrequency range tend to be more annoying (Goldstein, 1994).

Figure 2. Standard A, B, C, and D filter characteristics for sound level meters (IEC 179, 1973a; IEC 179a, 1973b).

The weighting curves, A to D, have broader applications than, for example, for evaluating the risk of damage to hearing and the sound pressure level of traffic noise. The efforts to describe the effect of noise in the simplest possible way, that is, in terms of a one-figure value, have resulted in a number of proposals for weighting, and, apart from the weighting curves A, B, C, and D, also to various noise indices (e.g., Kryter, 1985, 1994), for example, the Noise Rating numbers (NR) and Noise Criteria (NC). However, the weighting curves were all developed for stationary or quasi-stationary sound exposures and may, therefore, easily give rise to more or less serious errors in other community-noise applications.

The weighting curves A, B and C are a compromise between the American and German standards of the mid 1950's so that the tolerance limits of the new curves included the nominal values of both standards. The A-curve was based on the 40 phon equal loudness contour and was recommended for use for loudness levels between 20 to 55 phon.

The A-weighting is widely used for sound level measurements in a variety of situations. For sounds of narrow frequency range, considerable care must be exercised in the interpretation of A-weighted sound pressure level readings, since they may not accurately reflect the loudness of the sound. It should be noted that the A-filter has been adopted so generally that sound pressure levels frequently quoted in the literature simply in dB are in fact A-weighted levels. Furthermore, many older general purpose sound level meters are restricted solely to A-weighted sound pressure level measurements.

King (1941) was perhaps the first to suggest a calculation method for predicting (perceived) loudness from octave band analysis of complex sounds. Many years later, two different calculation methods for loudness were developed and standardized (ISO R532, 1966; ISO 532, 1975b): Method A (according to Stanley S. Stevens) using 1/1 octave analysis and Method B (according to Eberhard Zwicker) using 1/3 octave analysis data.

3.4 The Time Factor

Sounds can appear to be steady to human hearing because the auditory averaging time is inherently long, much longer than the acoustic cycle times.

Similarly, sound level measurements can be made to appear steady by selecting a suitably long averaging time. In precision sound level meters, the "slow" response time (1.0 s) is appreciably longer than the auditory averaging time and is used to obtain a steady reading, when the signal level fluctuates at a rapid rate. The "fast" response time is considered to be of similar order as that of the auditory system (0.125 s). However, in noise assessment, sound level fluctuations are usually ignored and, therefore, the "slow" response time is commonly applied. Difficulties arise when these readings vary significantly with time, as they do in many environments. Often, such level fluctuations are small but in some situations, for example, near to roads and airports the fluctuations can be measured in tens of dB; the rate of fluctuation can also vary widely. For impulsive sound, often the time-weighting "impulse" is used (0.035 s).

Series of sound events or intermittent sound are described in various ways: Percentiles of the occurrence, per cent in excess of defined sound pressure level, Noise and Number Index (NNI), etc. The dynamic characteristics of noise measurements are described in detail in IEC 651 (1979) with, i.a., integration time, bandwidth and handling of short signal impulses. It should be emphasized that sound pressure level as measured with meter setting "impulse" is based on loudness level, originating from perceptual measurements. Therefore, in order to assess the risk for damage to hearing the instantaneous "peak" may instead be measured directly and not, for example, the maximum sound pressure level. The IEC-standard for sound level meters adduces four different classes of accuracy 0, 1, 2 and 3, where 0 describes the most accurate instrument.

For a determination of the equivalent continuous sound pressure level (see section 3.5.1), for example by A-weighting over the period T hours (LAeq,T), the instrument should be used in accordance with IEC 804 (1985).

3.5 Noise Exposure Scales

In many noise measures and indices that are correlated with perception or other effects of interest, various underlying acoustic and nonacoustic (physical) properties have been combined in different ways. The basic objective of measurement is then to quantify overall noise exposure in the simplest possible terms. The physical characteristics of a noise which, on the basis of intuition and laboratory experiment, might be expected to influence its perception include the following: loudness level (recognizing average and peak values together with impulsive characteristics where appropriate), total noise "dose", amplitudes of level fluctations, rates of fluctuation, number of noise events and duration of events, and duration of total noise exposure.

Clearly, the acoustic stimulation alone have many dimensions; the following three procedures are most commonly used to measure some of them.

3.5.1 Equivalent Continuous Sound Pressure Level

To measure an average sound pressure level the meter averaging time is extended to equal the period of interest, T, which may be an interval in seconds, minutes, or hours. This gives a dB-value in Leq which stands for equivalent continuous sound pressure level; or according to a forthcoming standard by IEC should be named the "time average level". It is derived from the following mathematical expression in which A-weighting has been applied:

$$L_{Aeq,T} = 10 \log_{10} \left[(1/T) \int_0^T 10^{[L_{pA}(t) / 10dB]} \, dt \right] \qquad (6)$$

Because the integral is a measure of the total sound energy during the period T, this process is often called "energy averaging". For similar reasons, the integral term representing the total sound energy may be interpreted as a measure of the total noise dose. Thus, Leq is the level of that steady sound which, over the same interval of time as the fluctuating sound of interest, has the same mean square sound pressure, usually applied as an A-frequency weighting (Eq. 6). The interval of time must be stated.

Equivalent continuous sound pressure level is gaining widespread acceptance as a scale for the measurement of long-term noise exposure. For example, it has been adopted by the ISO for the measurement of both community noise exposure (ISO 1996, 1982, 1987,a, 1987c) and hearing damage risk (ISO 1999, 1990). It also provides a basis for more elaborate composite noise indices discussed in subsequent sections of this document including the day-night weighted sound pressure level (L_{dn}).

Following the introduction of jet aircraft into commercial service, it was suggested that the then existing loudness scales were inadequate for aircraft noise assessment purposes. An alternative scale of Perceived Noise Level (PNL) was, therefore, developed, with the unit dB(PN) (Kryter, 1959, 1985, 1994). This scale was derived using the equal loudness level procedure of S.S. Stevens (1956, 1972) but instead based on the attribute of perceived noisiness (defined as the "unwantedness" of the sound) that was considered different and more relevant to aircraft noise than loudness. In fact, the only difference between the calculations involved is the use of different frequency response curves. As research progressed towards legislations for aircraft noise emission control (U.S. Federal Aviation Regulations, 1969; see also ICAO, 1993), the perceived noise level scale was modified to include special weightings for "discrete frequency components", that is, irregularities in the spectrum caused by the noticeable periodic components of engine fan and compressor noise, and the duration of the sound (Kryter & Pearsons, 1963). This modified quantity, known as Effective Perceived Noise level, is expressed in dB(EPN).

Because PNL could not be measured with a simple meter, the D-weighting filter constituted a parallel development. Its characteristics were based on an equal noisiness (rather than an equal loudness) frequency response curve (IEC 537, 1976; D-weighting now withdrawn by IEC). This weighting circuit is available in some sound level meters and is intended for aircraft noise monitoring purposes.

The equivalent continuous sound pressure level, expressed in dB LAeq,T is unsuitable as a measure of value for predicting long-term adverse effects, that is., owing to the fact that the distribution over time of exposure does not appear and that the temporal profile is not stated. A number of proposals for corrections due to time have been presented: number of events, time of day, statistical distribution, number of heavy vehicles passing, Noise Number Index, etc. (e.g., Kryter, 1985; Zwicker & Fastl, 1990).

3.5.2 Level Distribution

A widely used method of recording the variations in sound pressure level is that of level distribution analysis, sometimes called statistical distribution analysis. This yields a graph of the percentage of the total time for which any given sound pressure level is exceeded; such information can be summarized by reading specific levels from this graph. For example, L_{10}, L_{50}, and L_{90}, the levels exceeded for 10, 50, or 90 % of the time, are frequently used as average measures typical for the "maximum", "median", and "background" levels, respectively. The same statistical approach is used to describe the distribution of loudness values in $N_{5,}$ (Fastl, 1993), N_{10} (Berry & Zwicker, 1986) or N_{50} (Watts, 1991).

3.5.3 Limitations of A-Weighted SPL as a Measure of Loudness or Ann

As pointed out by Hellman and Zwicker (1982), A-weighted SPL was first introduced into a sound level meter in 1936. Due to its simplicity and convenience, the A-weighting has become a popular and often useful frequency weighting also for assessing the perceived magnitude of noise. However, for many years international commissions have been aware that dBA is an overall value which may simulate neither the spectral selectivity of human hearing nor its nonlinear relation to sound intensity. Thus, if sounds with different spectral envelopes are compared (e.g., various community noises), the dBA-value obtained may be an inaccurate indicator of human subjective response. Human hearing is possible to simulate much better via computer software or/and signal processors.

In the past, sound pressure level has been measured widely by A-weighting. At the same time, both in the laboratory and in the field evidence has accumulated that A-weighting predicts loudness and annoyance of community noise rather poorly. Not only does A-weighted sound pressure level underestimate the impact of the low-frequency components of noise (Goldstein, 1994), but it is also strongly dependent on the exposure pattern with time. For sounds that exceed 60 dB the reliability of A-weighting decreases. Moreover, A-weighted sound pressure level neither considers the effects of mutual masking among the components in a complex sound nor the asymmetry of masking patterns produced in the auditory system (Zwicker & Fastl, 1990). Yet, despite these well-known limitations, the A-weighted sound pressure level is widely used in practice.

The A-filter is unrepresentative of the loudness of sounds containing a mixture of noises and tonal components. In such cases, A-weighted sound pressure level is less suitable for the prediction of loudness or annoyance. That is also true for noise containing most of its energy in the low-frequency range of 15-400 Hz. It may then underpredict perceived loudness by 7 to 8 dBA, relative to a 1,000 Hz target noise (Kjellberg & Goldstein, 1985). The reason is that loudness increases due to bandwidth increase and that spectrum shape is not accounted for to a satisfactory degree by the A-filter (cf. Zwicker, 1987). A decrease in A-weighted sound pressure level can result in a corresponding increase in loudness (Hellman & Zwicker, 1982) or annoyance. This clearly reveals the shortcoming of using overall SPL, either unweighted or A-weighted, as an indicator of loudness and annoyance.

4 TYPES OF ENVIRONMENTAL NOISE

4.1 Introduction

Noise is a problem that affects everybody. Noise is likely to continue as a major issue well into the next century. To understand noise we must understand the different types of noise, where noise comes from, the effect of noise on humans and the various ways we have of measuring both the sound as a cause of noise and the noise effects. This chapter describes the various types of noise that can affect the community and offers some basic definitions used in measuring sound for assessing the expected effects.

Sound is produced by a mechanical disturbance spreading out as a wave motion in the air at a speed of about 330 m/s. Acoustic waves entering the ear evoke a physiological response which causes nerve impulses to be transmitted to the brain. The brain interpret these impulses so that they can be perceived as sound.

Noise is unwanted sound and thus implicitly refer to a subjective classification of sound. Sound can have a range of different physical characteristics, but it only becomes noise when it has an undesirable physiological or psychological effect on people. Nevertheless, it is important to understand the physical characteristics of sound since these characteristics determine the various ways we have of measuring and describing sound.

The main physical characteristics are: sound pressure level, sound frequency, type of sound, and variation in time. Typical sound pressure levels range from about 20 dB LAeq in a very quiet rural area to between 50 and 70 dB LAeq in towns during the day time, to 90 dB LAeq or more in noisy factories and discotheques to well over 120 dB LAmax near to a jet-aircraft at take-off.

An audiofrequency is associated with the perception of the pitch of a tonal sound. Sound frequency is measured by the number of repeated cycles of the sound wave in one second (c/s or Hz) and the audible frequency range is 20-20,000 Hz. An idling diesel engine can produce large amounts of low frequency sound in the range of 20 to 150 Hz, whereas a warning siren usually produces a medium to high frequency sound typically around 2,000 Hz. The sound design of warning signals is based on the fact that the human auditory system is most sensitive in the middle range of frequencies from 1,000 to 4,000 Hz. Sound pressure level weighted with A-, B-, and C-filters in sound level meters is intended to take into account part of the differential frequency sensitivity.

Type of sound describes the particular features of a sound which makes it possible for a listener to identify it. The ability to identify the source is very important in determining community annoyance. These features can include tonal and harmonic qualities, impulsiveness, the relative balance of high and low frequencies and the steadiness or irregularity of the sound. There are a whole range of physical measurements which can express these different features in a more or less appropriate way for noise impact predictions.

Sound pressure levels normally vary with time. Rapid fluctuation in sound pressure level over less than 1 s can contribute to impulsiveness. Moving sound sources such as overflying aircraft or road vehicles produce a time-varying sound pressure level over event periods of typically 10 to 100 s. Noise from fixed installations, such as ventilation systems, can often be steady for much of the day, but may drop at night. The maximum A-weighted sound pressure level is described by the quantity LAmax and depends on the time constant set in the measurement instrument (“slow” or “fast”). Peak level is the peak of the instantaneous sound pressure oscillation in the time domain, not the maximum value of the effektive sound pressure (p_{rms}) or of the sound pressure level. Peak level is commonly expressed in dB by calculation (Eq. 3).

The equivalent continuous sound pressure level is described by the quantity LAeq,T (Eq. 6). In practice, adjustments (often called “penalty” factors) for various sound characteristics are sometimes introduced into noise indices, for example, for impulsiveness, tonal components, low frequency, and different time period (day/night). Such indices which are based on LAeq,T are sometimes called “rating scales” (Schultz, 1982a).

4.2 Sources of Noise

4.2.1 Machinery Noise, Noise from Industrial Plants and

Mechanized industry creates serious noise problems, subjecting a significant fraction of the working population to potentially harmful sound pressure levels of noise. It is responsible for high noise emissions indoors as well as outdoor of plants. In industrialized countries it has been estimated that 15-20 % or more of the working population is affected by sound pressure levels of 75-85 dBA. This noise is due to machinery of all kinds and often increases with the power of the machines. The characteristics of industrial noise vary considerably, depending on specific equipment. Rotating and reciprocating machines generate sound that is dominated by tonal and harmonic components; air moving equipment tends to generate sounds with a wide frequency range. The highest sound pressure levels are usually caused by components or gas flows that move at high speed (e.g., fans, steam pressure relief valves) or by operations involving mechanical impacts (e.g., stamping, riveting, road breaking).

In industrial areas, the noise usually stems from a wide variety of sources, many of which are of complex nature. Various types of machinery are involved and they represent artificial noises which are of concern because they may contain predominantly low or high frequencies as well as tonal components, they may be impulsive and also present unpleasant and disruptive temporal sound patterns.

Machinery that moves air are of special interest because it usually creates noise with a large component of low frequencies. Unlike noise containing mainly higher frequencies, low-frequency noise is less attenuated by walls or other structures and it can cross great distances with little energy loss due to atmospheric and ground attenuation.

In residential areas, noise may stem from mechanical devices (e.g., heat pumps and ventilation systems, traffic) as well as voices, music and other kinds of noises generated by neighbors (e.g., lawn movers, vivid parties, and other social activities). Due to low-frequency characteristics, noise from ventilation systems in residential buildings may cause considerable concern even at low and moderate sound pressure levels.

Sound generation mechanisms of machinery are reasonably well understood. The technical requirements for low noise output in new machinery can usually be specified but the noise declaration of machinery, which describes the noise output of the machine, is not yet used efficiently. The noise declaration should preferably be used for selecting and purchasing the machine which is least noisy. The difficulty of reducing the sound output and the noisiness of existing equipment is a serious obstacle to the improvement of working environments (e.g., jack hammer or shooting range). Machinery should preferably be silenced at the source.

Noise from fixed installations such as factories or construction sites, heating pumps and ventilation system plants on roofs, can also affect the nearby communities. To reduce the sound output from such sources, either the use of quieter plant and equipment is encouraged, or through zoning to separate industrial land uses from the more noise-sensitive residential areas. As last resorts, insulation or restriction of operation time may be used.

4.2.2 Transportation Noise

4.2.2.1 Road traffic

The noise of road vehicles is mainly generated from the engine and from frictional contact between the vehicle and the ground and air. In general, road contact noise exceeds engine noise at speeds higher than 60 km/h. The sound pressure level from traffic can be predicted from the traffic flow rate, the speed of the vehicles, the proportion of heavy vehicles, and the nature of the road surface. Special problems can arise in areas where the traffic movements involve a change in engine speed and power, such as at traffic lights, hills, and intersecting roads.

4.2.2.2 Rail traffic

Railway noise depends primarily on the speed of the train but variations are present depending upon the type of engine, wagons, and rails. Impact noises can be generated in stations and marshaling-yards because of shunting operations. The introduction of high speed trains has created special noise problems. At speeds greater than 250 km/h, the proportion of high frequency sound energy increases and the sound can be perceived as similar to that of overflying jet aircraft.

4.2.2.3 Air traffic

Aircraft operations have caused severe community noise problems over the past 20 to 30 years. The introduction of the early turbojet transport aircraft led to a surge of community reactions against commercial and military airports. More research has been devoted to aircraft noise than to any other environmental noise problem (B. Berglund, Lindvall, & Nordin, 1990).

The main mechanism of noise generation in the early turbojet aircraft was the turbulence created by the jet exhaust mixing with the surrounding air. This noise source has been significantly reduced in modern high by-pass ratio turbo-fan engines which surround the high velocity jet exhaust with a lower velocity airflow generated by the fan. The fan itself can be a significant noise source, particularly during landing and taxiing operations. Fan noise can be controlled to a certain extent by providing acoustic absorption in the fan cowling. There is some concern over the possible use of advanced multi-bladed turbo-prop engines in the future, as these engines can produce relatively high levels of tonal noise. Aircraft takeoffs are known to produce intense noise including vibration and rattle but also landings cause noise annoyance especially when reverse thrust is applied. In general, larger and heavier aircrafts produce more noise than lighter aircrafs.

The smaller aircraft types as used for private business, flying training and leisure purposes can cause particular noise problems near to general aviation airports. Leisure flying at weekends can cause difficulties because nearby residents are more likely to be at home. Airports hosting many helicopters often create a specifically severe noise problem.

4.2.2.4 Sonic booms

The sonic boom is a shock wave system in air generated by an aircraft, when it flies at a speed slightly greater than the local speed of sound. The shock wave extends from an aircraft throughout supersonic flight in a roughly conical shape. At a given point, the passage of the shock wave causes an initial sudden rise in atmospheric pressure followed by a gradual fall to below the normal pressure and then a sudden rise back to normal. These pressure fluctuations, when recorded, appear in their typical form as so-called N-waves. When they occur with a separation greater than about 100 ms, the sonic boom has a characteristic double sound. High intensity sonic booms can damage property. Lower intensity sonic booms can cause a startle response in people as well as animals. The startle response is a secondary effect due to the sudden and unexpected exposure. The sonic boom can be heard as a very loud and boomy sound.

An aircraft in supersonic flight trails a sonic boom that can be heard up to 50 km on either side of its ground track depending upon the flight altitude and the size of the aircraft (C.H.E. Warren, 1972).

4.2.3 Construction Noise, Public Works Noise and Military Noise

Building construction and earth works are activities that can cause considerable noise emissions. A variety of sounds is present from cranes, cement mixers, welding, hammering, boring, and other work processes. Construction equipment is often poorly silenced and maintained, and building operations are sometimes carried out without considering the environmental noise consequence. Street services such as garbage disposal and street cleaning can cause considerable disturbance if carried out at sensitive times of day.

In certain instances, military activities may be an important noise source such as noise produced by heavy vehicles (tanks), helicopters, and small and large fire arms. Noise from military airfields may present particular problems compared to civil airports, for example, if used for training interrupted landings and takeoffs (so-called touch down).

4.2.4 Building Services Noise

Building service noise can affect people both inside and outside the building. Ventilation and air conditioning plants and ducts, heat pumps, plumbing systems, and lifts, for example, can compromise the internal acoustic environment and upset nearby residents.

4.2.5 Domestic Noise

Noise from neighbors is often one of the main causes of noise complaints. These complaints are largely due to the inconsiderate or thoughtless use of powered domestic appliances (vacuum cleaners, washing machines, lawn mowers, etc.), systems for music reproduction, TV sets, or hobby activities. Substantial societal problems, more infrequent but nonetheless important, are caused by disturbing noise emanating from neighbours and their social activities.

4.2.6 Noise from Leisure Activities

The possibilities of using powered machines in leisure activities are increasing all the time. For example, motorracing, off-road vehicles, motorboats, water skiing, snowmobiles, etc., can all contribute significantly to loud sound pressure levels in previously quiet areas. Shooting activities not only have considerable potential for disturbing nearby residents, but can also damage the hearing of those taking part. Even tennis play and church bell ringing can lead to noise complaints.

Discotheques and rock concerts may exceed hearing damage risk criteria for the musicians, employees and the audience. This sometimes applies also to outdoor concerts. Careful attention to the design of the building can substantially eliminate neighborhood noise problems caused by discotheques. But, there can still be a noise problem outdoors due to customers arriving and leaving.

The general problem of access to leisure activity sites often adds to the road traffic noise problems in particular areas.

5 EXPOSURE TO ENVIRONMENTAL NOISE

Sound waves travel from source to receiver through a variety of media. Outdoors it will be through the atmosphere and will then be influenced by wind turbulence and gradients, air temperature, ground reflections, etc. The amplitude, the spectrum as well as the duration of the sound will be affected. For instance, the sound will be attenuated by air absorption, fog, rain or snow, barriers such as walls and buildings, and by ground effects. However, under certain circumstances, attenuation may not take place, for example, wet snow on ground or at night for thin growth of trees and shrubs.

Indoors noise may travel through the air and the structure of the building and be modified by the sound insulation of walls and windows, the reverberation time of the space, and the design and surface materials of the room. A frequent problem is the transmission of sound from one dwelling to another or even between rooms in the same dwelling. Many dwellings are not adapted to the large diversities in social activities among age generations or to time of the day. Aberrant social behavior is a well recognized noise problem in multi-flat dwellings. Noise from the ventilation system is a common source of complaints.

The extent of the noise problem is large. In the EU countries about 40 % of the population are exposed to road traffic noise with an LAeq,T exceeding 55 dB daytime and 20 % are exposed to levels exceeding 65 dB (Lambert & Vallet, 1994). Taking all exposure to transportation noise together about half of the EU citizens are estimated to live in zones which do not ensure acoustic comfort to residents. More than 30 % are exposed at night to noise levels exceeding 55 dB LAeq which are disturbing to sleep.

It is no surprise that annoyance to community noise is widespread among citizens: in some EU-countries 20-25 % are being annoyed by road traffic, 2-15 % by aircraft, and 2-4 % by railway noise (Lambert & Vallet, 1994).

Until now the introduction of noise emission standards for vehicles have had limited impact on the exposure to road traffic noise (Sandberg, 1993). Traffic planning and correction policies may diminish the number of people exposed to the very high community noise levels (>70 dB LAeq) but the number exposed to moderately high levels (55-65 dB LAeq) continues to increase in industrialized countries.

A substantial growth in air transport in Europe is expected in the future; in the U.K. by 50-80 % in passenger movements over ten years. General aviation noise at regional airports will increase (Large & House, 1989). However, at the same time jet aircrafts may become 8 to 12 dB quieter due to regulation. An outlook for exposure to noise has been made by OECD (1991). The number of noise sources is expected to increase and is likely to be accompanied by a deterioration of the noise environment. At the same time, it is expected that the public will become more aware of noise pollution and also be protected from noise problem. The OECD (1991) identifies the following four factors of increasing importance in the future:

(1) Expanding use of increasingly numerous and powerful sources of noise.

(2) Wider geographical dispersion of noise sources together with greater individual mobility and spread of leisure activities.

(3) Increasing spread of noise over time particularly in the early morning, evenings and weekends.

(4) Increasing public expectations which are closely linked to increases in incomes and in education levels.

The OECD (1991) report forecasts (a) a strengthening of present noise abatement policies and their applications, (b) a further sharpening of emission standards, (c) a coordination of noise abatement measures and transport planning, particularly designed to reduce mobility, and (d) a coordination of noise abatement measures with urban planning.

High-level noise exposures giving rise to noise-induced hearing deficits are by no means restricted to occupational situations. Such levels can also occur in concerts, discotheques, motor sports, shooting ranges, and leisure activities. Other sources are also important such as music played back in headphones and impulse noise from toys and fireworks. It has also been argued that community noise exposure would be a contributing factor to hearing deficits with increasing age. The existence of such a “sociacusis” waits for final scientific verification since so many other factors and agents are also influencing hearing.

The acoustics of a space designed for speech must primarily ensure clarity and intelligibility. Therefore it is important to design spaces for optimum reverberation time and spatial-temporal aspects including the time delay between the direct and first reflected sound.

Planners need to know the likely effects on the noise pollution in a community of introducing a new noise source as well as increasing the level of an existing source (Diamond & Rice, 1987). There are a number of models to predict annoyance due to a combination of noise sources, such as models of energy summation, of source addition, of source difference, of response summation and response inhibition, and of the (subjectively) dominant source (e.g., Vos, 1992a). Policy makers, when considering applications for new developments, must take into account maximum levels, equivalent levels, frequency of occurrence, and operating time of the major noise sources.

6 ANATOMY, PHYSIOLOGY, AND PSYCHOPHYSICS OF THE AUDITORY SYSTEM

The auditory system is a complex comprising the outer ear, middle ear, cochlea of the inner ear, the connection to the brain through the auditory nerve, and pathways within the brain. Detailed descriptions of the auditory system are found in articles by, for example, Flock (1971), Pickles (1982), and Møller (1983).

6.1 The Outer and the Middle Ear

The outer ear collects sound waves through the auricle (pinna) and the external acoustic meatus which ends with the tympanic membrane (eardrum). The auricle is particularly important for high-frequency directional hearing. The collected sound waves causes a resonance vibration of the eardrum. Transmission is nonlinear which may lead to frequency specific effects. In the middle ear the vibration is transmitted by a chain of three bones (malleus, incus, stapes), (cf. Møller, 1961). The ossicles connects with the inner ear through a window in the cochlea known as the “oval window”. An alternate sound conduction pathway to the inner ear is via bone conduction involving the mastoid bone and the skull.

The so-called middle ear muscle reflex plays a significant role in the effect of noise particularly in regard to masking, loudness, and auditory fatigue. This aural reflex is mediated by two small muscles in the middle ear, the tensor tympani and stapedius, which are attached to the small bones (malleus and stapes) that connect the ear drum with the cochlea. When intense sound occur (above 80 dB), or objects touch the external ear canal, these muscles contract pulling the stapes and tympanic membrane towards the middle ear cavity putting increased resistance to movement into the ossicular chain. This protects the ossicles from excessive movement and damage to themselves and the cochlea. But there is a finite delay in this occurring and impulsive sounds, with a rapid rise time, may be too quick for the reflex to come into operation. The ear then responds in a different way and is more susceptible to damage. For protective criteria, the “peak” level is used. As stated before this is unweighted.

The aural reflex is more responsive to broad band sounds than to pure tones and more responsive to lower frequencies than to higher, and is most readily activated and maintained by intermittent, intense impulses (Borg & Courter, 1989). The middle ear muscle contraction increases the impedance of the middle ear resulting in an attenuated input of sound energy through the cochlea.

6.2 The Cochlear Mechanisms

The cochlea contains the organ of Corti which is located between two fluid-filled chambers. Impulses arise as a result of pressure waves displacing the organ of Corti in response to vibration produced at the oval window of the cochlea. The organ of Corti contains sensory cells, which convert the pressure wave into ionic and electric events which constitute a nerve impulse. The sensory cells have hair-like projections (stereocilia). There are two groups of hair cells located on the basilar membrane of the organ of Corti. The inner hair cells serve as the pre-synaptic sensory receptors which connect to the afferent Type I spiral ganglion nerve cells. The outer hair cells, which are more commonly damaged by noise and ototoxic agents, are believed to serve as an amplification system due to their contractile properties, and their efferent innervation.

According to von Békésy (1960), a particular region of the basilar membrane responds by maximal vibration depending on the frequency of the sound. When the stereocilia of the inner hair cells are bent there is an initiation of action potentials in the sensory nerve endings. The brain interprets the impulses from the place of maximal stimulation of the organ of Corti as a particular pitch of sound (place pitch). This localization is enhanced by the inhibitory effect of centrifugal nerve signals and feedback circuits in the central pathways. Up to a certain frequency range, nerve impulses are time-locked with periods of sound wave (rate pitch).

When the sound intensity increases, an ever larger region of the basilar membrane will become involved and more hair cells are being activated.

Prolonged exposures to intense sounds may cause degenerative changes in the organ of Corti.

6.3 The Auditory Pathway and the Brain

Neural information is conducted by means of the acoustic (8th) nerve from the organ of Corti to the brain. The pathway to the cerebral cortex involves synaptic relays and the transmission of acoustic information to the cortex of the brain is rather complicated. A number of nuclei have been identified that are connected to form complex integrated systems. The auditory pathway projects on the auditory cortex of the temporal lobes of the brain. Many aspects of auditory processing take place in the cochlea, peripheral auditory nerve and brainstem. Advanced analysis of acoustic stimuli involving recognition and interpretation of sounds occurs in the auditory association cortex. At certain levels of the auditory pathway there are links between the two sides of the brain. Thus, a lesion on one side of the brain is often insufficient to be detected in audiometric testing. The discrepancy in time of arrival of the stimulus in the left and right ear and the inter-aural sound level difference, which is encoded primarily at the level of the brainstem, mainly determines the direction and distance of the sound source.

There are also descending, efferent neurons which provide feedback circuits, producing the possibility of inhibition. The central nervous system also controls part of the initiation of nerve impulses in the organ of Corti.

The transmission of neural data to the brain from the sensory hair cells is not just a simple relay to the cortex of the brain. At all steps of this pathway a complex processing takes place which is important to a number of sound qualities such as perceived intensity, perceived pitch, speech feature analysis, and noise identification. The feedback inhibition is especially important for auditory sharpening. Connections to the reticular activating system of the mid-brain are particularly important for the arousal function. It is assumed that the central inhibition suppresses the background noise when one is concentrating on a particular acoustic signal. The auditory system also has connections to motor and autonomic centers of the brain.

6.4 Psychoacoustics

The perceptual attributes of simple sounds mainly include loudness, pitch, timbre, and temporal extent. These correspond to combinations of levels of stimulus intensity, frequency, and duration. The relationship between the physical and perceptual attributes of sound are explored in psychophysical experiments.

6.4.1 Detection of Sounds

The absolute threshold refers to the physical intensity or air pressure of a sound, which elicits a sensation on a specified portion of the occasions on which it occurs (usually 50 %) whereas on the other occasions no sensations are experienced. To understand threshold psychophysics one must make a distinction between traditional psychophysical theory and contemporary information processing theory. Traditional psychophysics puts its main emphasis on the effect of the stimulus (e.g., sound) and on threshold values dividing a physical continuum (sound intensity) into those values that elicit a sensation and those that do not.

It is important to note that the proponents of traditional theory believed the boundary between these values to be fixed at any one moment (the absolute momentary threshold). The traditional model is analogous to the case when sensory transducers function like "smoke detectors". The basic point made in this regard by contemporary information processing theorists is that there really are no such cutoffs (stimulus threshold values). The Signal Detection Theory argues that the observer always interprets his sensory experiences and decides whether they are caused by a certain stimulus or other factors (e.g., spontaneous neural activity). The decision is determined by the observer's experience with the stimulus situation and his attitudes (e.g., D.M. Green & Swets, 1966; Baird & Noma, 1978). The perception of traffic noise would be different for an automobile manufacturer and a citizen who does not like automobiles. Therefore, the outcome of a threshold test will depend partly on the stimulus value and partly on the observer's response criterion. This limits the usefulness of statements of psychophysical threshold results expressed purely in physical stimulus terms. The observation is particularly important in field research where it is impossible to control variables that affect the response criterion. This must be considered in any development of methodology of threshold measurement.

In spite of the theoretical ambiguity of the threshold concept, the threshold of hearing has become a conventional and useful measure of hearing sensitivity and impairment. Since in everyday life sounds are nearly always well above normal threshold, hearing threshold level is primarily useful as a predictor variable. In fact, it predicts auditory performance on speech tasks as well as many other tasks remarkably well even though its effect is only indirect (King, Coles, Lutman, & D.W. Robinson, 1992).

6.4.2 Psychophysical Relationship for Loudness

The prediction of loudness from the physical analysis of different complex sound sources has long been a goal of applied psychoacoustics. Several loudness-evaluation procedures have been proposed (see e.g., Scharf, 1978). The most common are based on weightings of the complete frequency spectrum and are applied as filters in sound level meters. Others are calculation methods for predicting the loudness of complex sounds, and they are usually based on loudness summation of continuous octave or fractional octave bands (e.g., Mark VI, S.S. Stevens, 1961a; see Mark VII, S.S. Stevens, 1972) or critical bands (e.g., Zwicker, 1958). A compilation of studies and a comparison of methods for evaluating (perceived) loudness (or perceived noisiness or annoyance) was performed by Scharf, Hellman and Bauer (1977) and Scharf and Hellman (1979, 1980). The analysis include those procedures that relies on spectral sound properties; among these, S.S. Stevens's (1961a) Mark VI was found to be the best predictor. The ISO has recommended Mark VI as a method for calculating the loudness of complex sounds (ISO R532, 1966; ISO 532, 1975).

As a rule of thumb, people agree that when moderately intense single component sound such as a tone or a band of noise is raised in intensity by about 10 dB, it sounds twice as loud. This is consistent with the psychophysical power function (S.S. Stevens, 1957a, 1957b) that relates loudness to sound energy,

$$\Psi = a\, I^{n} \tag{7}$$

where Ψ stands for loudness perceived and I stands for physical sound intensity and a is a multiplicative constant related to the units of measurement. The exponent n is approximately 0.3 for tones and narrow-band noise (S.S. Stevens, 1975) and somewhat lower (Å0.2) for various community noises (e.g., B. Berglund, U. Berglund, & Lindvall, 1976).

Loudness not only depends on sound energy but also on frequency and other physical parameters. At moderate levels, low-frequency sounds (those below 900 Hz) are judged to be less loud than high-frequency sounds (those between 900 to 5,000 Hz) when sounds are of equal physical intensity. The frequency weighting function, referred to as A-weighting, was developed to simulate this effect at low sound levels and for pure tones. It is well known that with the use of this weighting it is necessary to use different level limits for different types of sources. Not only the source itself but also the listener's attitude is of importance.

The A-weighting function is widely used to obtain index measures of community noise. One should realize, however, that a single weighting function used for various sound pressure levels cannot reflect the perception or other adverse effects of different noises. For example, two sources of community noise that are equal in dBA may differ substantially in loudness (e.g., B. Berglund, U. Berglund, & Lindvall, 1975a, 1976; Goldstein, 1994).

The loudness of a complex sound is the sum of the loudnesses of the individual components only if these are widely spaced on the frequency continuum and about equally loud (e.g., Marks, 1978). When the components are not widely spaced, or differ greatly in loudness, mutual inhibition and perceptual interference result in the total loudness being less than the sum of the loudnesses of the components. This knowledge has led to the development of Stevens's and Zwicker's procedures for calculating total loudness from physical sound measures (S.S. Stevens, 1961a, 1972; Zwicker & Scharf, 1965). Several studies have been conducted to evaluate the adequacy of these procedures. They do not hold uniformly for all types of stimuli; they are especially weak in predicting loudness of sounds with strong tonal components, discontinuous spectra, and impulsive time structures. For example, one experiment showed that while Stevens' Mark VI accurately predicted loudness of white noises, it failed to predict the loudness of power line noise (B. Berglund, U. Berglund, & Lindvall, 1986a). This study seems to be the only one that actually tried to use the Mark VI formula with loudnesses of octave bands to predict the loudness of a real community noise.

The conclusion is that the equal loudness contours based on broad-band noise often are not applicable to community noises. However, Zwicker's procedure (ISO 532, 1975) has been shown to be able to handle tonal components reasonably well, better than Stevens's procedure (Hellman, 1991). Furthermore, Zwicker's procedure has been demonstrated to give accurate predictions of (percepeived) loudness for various kinds of community noises, and in addition, surprisingly good performance was shown for complex impulse noises such a shots from rifles or sounds from cannons (B. Berglund, U. Berglund, & Lindberg, 1986).

For many years, regulatory authorities have concentrated on loudness as the sole component responsible for annoyance. In such a case, noise control would be relatively straightforward. However, there are other psychological and physical characteristics of complex sounds that may be more relevant, for example, the intrusiveness of sound (Fidell, Teffeteller, Horonjeff, & D.M. Green, 1979; Fidell & Teffeteller, 1981; Preis, 1987), their sharpness (e.g., Aures, 1985) and fluctuation strength (e.g., Zwicker & Fastl, 1990).

6.4.3 Masking

Auditory masking is defined as the decrease in audibility of one sound due to the presence of another sound (e.g., Bilger & Hirsh, 1956). There is total as well as partial masking, the latter being characterized by reduced loudness. Usually, masking is expressed as a change in the detection threshold value. Thus, according to the Acoustical Society of America (ANSI, 1994) masking has been defined as: (1) The *process* by which the threshold of audibility for one sound is raised by the presence of another (masking) sound; (2) The *amount* by which the threshold of audibility of a sound is raised by the presence of another sound. The unit customarily used is the decibel.

The concept of masking commonly refers to the case when the masker and the masked sound occur at the same time within the same critical band (see section 6.4.4). There are various other kinds of masking phenomena. Therefore, the ASA-definition needs to be expanded in order to include phenomena like partial masking (Scharf, 1971), central masking (Zwislocki, 1971), remote masking (Bilger, 1966), and nonsimultaneous (forward and backward) masking (Elliot, 1971). The masking phenomena depend on many factors. For example, remote masking refers to masking by frequencies well outside a critical band (see below). In addition, perceived loudness depends on frequency, bandwidth, intensity and degree of frequency spread but also on direct and remote masking. The time course of masking includes both a shorter period of backward and a longer period of forward masking (up to 30 ms).

6.4.4 Critical Band

As conceived by H. Fletcher (1940), the concept of filters within the ear, having what are called critical bands, has proved to be significant (Zwicker, Flottorp, & S.S. Stevens, 1957; Scharf, 1970). H. Fletcher (1940) assumed that to predict thresholds it would be reasonable to approximate the auditory filter as a simple rectangle with a flat top and vertical edges. Thus, all frequency components falling within the flat top, or pass band, would be passed equally whereas components outside the pass band would be rejected. He assumed (1) that the part of a noise that is effective in masking a test tone, is the part of the noise spectrum lying near the tone and (2) that masking is achieved when the power of the tone and the power of that part of the noise lying near the tone, and thus producing the masking effect, is the same. Parts of the noise outside the spectrum near the test tone do not contribute to masking. The approximation of the auditory filter as a simple rectangle works satisfactory for tones in broadband noise (the case used by H. Fletcher, 1940), but not for maskers that contain only a narrow range of frequencies (Egan & Hake, 1950).

The estimate of the critical band obtained by H. Fletcher is known in the literature as a “critical ratio”. The term “critical bandwidth” is reserved for more direct measurements of the bandwidth of complex stimuli or of maskers. In the frequency domain there is a critical bandwidth over which the ear processes loudness. Critical bands very in width, from about 100 Hz at the low-frequency end of the spectrum to 2.5 kHz at 10 KHz. It has been suggested that they represent equal distances along the basilar membrane (Greenwood, 1961; Zwicker, 1961; Scharf, 1970).

The critical bandwidth is used in sound measurement, the unit of which is given the name Bark. The scale relating frequency to number of Barks is called critical-band-rate scale and is used in loudness calculations according to the Zwicker method (ISO R532, 1966; see also ISO 532, 1975). However, an alternative approach is suggested by Moore and Glasberg (1983; see also Glasberg & Moore, 1990) to calculate loudness using the equivalent rectangular bandwidth (ERB) of the auditory filter instead of the critical bandwidth. In this model specific loudness at any point is the loudness per unit ERB-rate instead of critical-band-rate. The model has been shown to give good predictions for narrow-band -noise masking patterns but not for other conditions (van der Heijden & Kohlrausch, 1994).

In addition to loudness summation and masking, identification of features of complex sounds and detection of sounds of speech and music employ the above-mentioned and other frequency analyzing capacities of the ear. The critical band discussion is closely linked to the one of frequency selectivity (see section 6.4.7).

6.4.5 Temporal Summation

The critical summation time is the critical time period over which the auditory system summates intensity. Sometimes this period is called the time constant of the ear. It is about 300 ms for detection of pure tones in the quiet. Both absolute detection thresholds and loudness of sounds depend on duration. For durations exceeding about 500 ms, threshold is independent of duration but for durations between 20 and 200 ms, the sound intensity necessary for detection decreases as duration increases (Exner, 1876; von Békésy, 1960; D.M. Green, Birdsall, & Tanner, 1957). Over a reasonable range of durations, the auditory system appears to integrate the energy of the stimulus over time in the detection of short duration tone bursts (Garner & G.A. Miller, 1947; see also Plomp & Bouman, 1959). The decrement in loudness with decreasing duration is about a factor of 2 for durations from 100 to 10 ms (Zwicker & Fastl, 1990). However, the conclusions about the exact size of the time constant as well as the equal energy hypothesis due to time and intensity have been questioned in a critical review by Scharf (1978; see also Moore, 1982).

6.4.6 Adaptation and Habituation

The loudness of a steady sound does not adapt except under three conditions (Scharf, 1978; Canèvet, Scharf, & Botte, 1989): (a) loudness adaptation to a sound may appear near threshold, (b) when accompanied by an intermittent sound in the opposite ear (c) or in the same ear. Simple loudness adaptation, (as opposted to induced, see below) seems to occur independently in each ear, but only at low sound pressure levels (below 30 dB). It is suggested that simple loudness adaptation takes place in the peripheral part of the auditory system. The recovery appears to be rapid.

Induced adaptation, that is when a steady tone is accompanied by an intermittent tone to the other or the same ear, seems to be more prevalent than simple loudness adaptation (Botte, Canèvet, & Scharf, 1982). Induced adaptation in the same ear may result primarily from accumulated fatigue and be reflected in a high correlation with temporary threshold shift (Charron & Botte, 1988). The individual differences in loudness adaptation are large and the reason for this is unclear. Loudness adaptation should be classified as sensory adaptation, that is that the sensory system becomes less sensitive to prolonged stimulation. In consequence, the person is not able to perceive a stimulus as loud as when nonadapted.

Sensory adaptation is different from habituation which is considered to be a mental phenomenon. If a person habituates to a sound or noise, it means that (s)he get used to it and is not as aware of its presence as before the habituation took place. However, the person is able to perceive the sound whenever attending to it. Thus, in habituation the sensory sensitivity is unaffected which it is not in sensory adaptation.

In laboratory as well as community settings, many studies suggest that people do neither adapt nor habituate to noise (Scharf, 1983). There is no evidence of appreciable long-term adaptation or habituation in outcome of self-reported, traffic-noise annoyance, or tendency to focus attention on the noise (N.D. Weinstein, 1982). However, in a study of interventions in a traffic noise exposure situation, the change in dissatisfaction with the noise was considerably greater than would be predicted on the basis of findings for unchanged conditions (Griffiths & Raw, 1989). The effect of change was demonstrated to be persistent over a period of at least 2 years and a major part of it was visible over 7-9 years.

6.4.7 Frequency Selectivity

The capacity of the auditory system to separate out the frequency components of a complex auditory stimulus is known as frequency selectivity. The results of physiological experiments on tuning, the responsiveness of neurons to a range of frequencies, suggest that this function is accomplished mechanically within the basilar membrane. Tuning measured more centrally in the auditory pathway is no sharper than that found for the cochlea (Sellick, Patuzzi, & Johnstone, 1982)

Frequency selectivity may be investigated psychophysically by means of masking experiments, in which the critical masker intensity, allowing a predetermined level of detectability of a probe tone (e.g., 2,000 Hz), is determined for a set of masker frequencies on either side of the probe tone (e.g., 1,000, 1,250, 1,600, 2,500, 3,150, & 4,000 Hz). Normally, when the masker frequency is within a restricted frequency region around the probe tone, its intensity may be stronger athan the probe and still be tolerated. Thus, the function relating the critical intensity to the masker frequency, named the tuning curve, is V-shaped.

In general, the high frequency limb of the tuning curve above the probe tone is steeper than the low frequency limb below the probe tone (see Moore, Glasberg, & Roberts, 1984). Listeners with hearing loss due to cochlear dysfunction show abnormally broad tuning, evidenced by shallower tuning curves in the region of elevated hearing thresholds. This effect does not extend to the frequency region of normal hearing (Wightman, McGee, & Kramer, 1977).

6.5 Summary

Acoustical information is processed at all levels of the auditory system. While measurements and characterizations of the physical stimulus is feasible, the mental representation of these sounds reflects both passive and active processes. Some of these nonlinear processes are explicable by an understanding of the auditory system anatomy and physiology. More importantly, psychoacoustical principles provide a means of relating the physical features of sound to the psychological experience of hearing.

7 EFFECTS OF NOISE ON HUMANS

7.1 Noise-Induced Hearing Loss

7.1.1 Hearing Impairment

Normal hearing sensitivity is regarded as the ability to detect sounds in the audiofrequency range (about 20-20,000 Hz). However, individual hearing sensitivity varies. Some of these variations may be attributed to the effects of different environmental influences (J. Roberts & Bayliss, 1967); in industrialized countries, women generally have better hearing than men (Kylin, 1960; Dieroff, 1961a; Gallo & Glorig, 1964).

As a rule, hearing sensitivity diminishes with age, a condition known as presbyacusis (Glorig & J.C. Nixon, 1962). Consequently, corrections for aging should be considered when examining data on hearing loss caused by noise exposure. However, the literature reflects controversy concerning the degree to which cumulative effects of noise exposure in everyday life may contribute to eventual hearing loss (sociacusis; Glorig, Grings & Summerfield, 1958), thus obscuring the effect due to aging alone. Moreover, there is considerable variation between individuals in both the amount and rate of hearing loss due to aging. The general pattern of progression of presbyacusis has been quite well-established, and data are available in numerous reference sources (e.g., B.E. Weinstein, 1994). Loss of hearing sensitivity due to aging occurs mainly at the higher audiometric frequencies and is invariably bilateral (i.e., in both ears) and usually symmetric.

Present knowledge of effects of noise exposure on the auditory system is based primarily on laboratory studies on animals and occupational studies on human beings (CHABA, 1988; Katz, 1994). It is believed that noise can have metabolic consequences for the cochlea as well as produce mechanical trauma. The former are likely to be partially reversible while the latter are permanent. The first morphological changes found after noise exposure are usually fusing and bending stereocilia of the inner and outer hair cells in the cochlea (Axelsson & Lidén, 1985).

7.1.1.1 Hearing level, noise-induced threshold shift, and hearing impairment

In order to discuss the effects of noise on hearing, it is necessary to differentiate between hearing level (HL), noise-induced threshold shift (NITS), and hearing impairment. Hearing level refers to the audiometric threshold level of an individual or group in relation to an accepted audiometric standard (ISO 8253, 1989) and is sometimes incorrectly termed "hearing loss". Hearing level is a physical unit used to describe the output of an audiometer. Many audiological outcomes can be measured in terms of hearing level, such as hearing threshold, uncomfortable loudness level, and acoustic reflex threshold. When auditory thresholds are expressed in hearing level, they are termed hearing threshold levels (HTL). Hearing threshold levels outside the normal range indicate a hearing impairment. Hearing loss usually refers to a hearing impairment that is causing difficulties or to an hearing threshold level that has deteriorated (King et al., 1992). Noise-induced threshold shift is the quantity of hearing loss attributable to noise alone, after values for presbyacusis (including sociacusis) have been subtracted. These values may differ slightly according to where and how the presbyacusis data were collected (see for example Hinchcliffe, 1959; Gallo & Glorig, 1964; Spoor, 1967; US NCHS, 1987).

The fence for hearing impairment is generally referred to as the hearing level at which individuals begin to experience difficulty in leading a normal life, usually in relation to understanding speech (Smoorenburg, 1992; Abel, Krever, & Alberti, 1990). The fence for hearing impairment has been defined by the American Academy of Otolaryngology (AAO-ACO, 1979; see, e.g., Katz, 1994) as an arithmetic average of 26 dB or more hearing loss at the frequencies, 0.5, 1, 2 and 3 kHz (the definition is currently being revised); in Poland, it is defined as 30 dB or more at 1, 2, and 4 kHz (after age correction), and in the United Kingdom, it is 30 dB or more at 1, 2, and 3 kHz. It should be noted that a damage risk criterion of 30 dB at 1, 2, and 4 kHz may be more protective than a criterion of 26 dB at 0.5, 1, and 2 kHz, because hearing loss at high frequencies is usually greater than the loss at 500 Hz (WHO, 1980). However, the notion of a "fence" has uncertain scientific foundation. By some it is purely looked at as an administrative inconvenience to categorize subjects into those who may receive monetary compensation and those who are deemed not to have sufficient impairment. In fact, Smoorenburg (1992) suggests that all impairments down to 0 dB hearing level may make a difference to speech understanding. In some countries, the practice is that there should be no fence (King et al., 1992).

7.1.1.2 Noise-induced temporary threshold shift

A person entering a very noisy area may experience a measurable loss in hearing sensitivity but may recover some time after returning to a quiet environment. This phenomenon can be measured as a reversible or tem-

Figure 3. Hearing loss as a function of duration in noise exposure in years. Mean audio-grams for 203 miners, best ear tested. [a <1 year; b = 1-5 years; c = 6-10 years; d = 11-20 years; e = 21-30 years; f > 30 years; From: B. Johansson, 1952.)

porary shift in audiometric thresholds, and is called noise-induced temporary threshold shift (NITTS).

Recovery from NITTS depends on the severity of the hearing shift, individual susceptibility, and the type of exposure. If recovery is not complete before the next noise exposure, there is a possibility that some of the loss will become permanent. Recovery should not be judged solely by the audiogram, as there may be injuries which are not measurable psychophysically (Bohne, 1976). Information on NITTS has been used for two purposes: first, to predict sound pressure levels that could be permanently damaging to the ear, and second, to attempt to predict individual susceptibility to hearing loss caused by excessive noise. Measurements of NITTS are made by comparing pre- and post-exposure audiograms. The extent of NITTS, for the same exposure, varies considerably between individuals. Recovery, which is exponential, can take hours, days, or even weeks after exposure. It should be noted that NITTS can be experienced by individuals who already suffer from permanent noise-induced hearing losses. Thus, when assessing permanent damage, sufficient recovery time in the quiet should be allowed before audiometric tests.

7.1.1.3 Noise-induced permanent threshold shift

The typical pattern of noise-induced permanent threshold shift (NIPTS) usually involves a maximum loss at around 4,000 Hz. Because the loss is sensorineural, it is seen in both air and bone conduction audiograms.

Although noise-induced hearing loss is believed to occur gradually, usually over a period of years, an abrupt process cannot be ruled out due to lack of empirical data as well as theoretical considerations. The rate and extent of loss depends on the severity and duration of the noise exposure, but individual susceptibility also seems to have a considerable effect on the rate of progression. Noise-induced losses are rather similar to losses due to aging and the two types of losses are difficult, if not impossible, to distinguish. A model relating presbyacusis and NIPTS has been proposed by Corso (1992). Fig. 3 shows the progression of noise-induced hearing loss observed in workers with increasing duration of exposure to intense noise levels (B. Johansson, 1952; see also, e.g., Abel & Haythornthwaite, 1984).

The first stages of noise-induced hearing loss are often not recognized because they do not impair speech communication ability in quiet. As the loss becomes greater, difficulty in speech reception may be encountered, particularly in noisy surroundings.

Hearing of important sounds other than speech, such as door bells, telephones, or electronic signals, may also be impaired. With further loss in hearing, speech communication may be severely affected.

7.1.1.4 Noise-induced permanent hearing loss

The prevalence of hearing loss among workers in noisy industries has been recognized since ancient times, and excessively loud noises are popularly described as deafening. Clinical observations of noise-induced hearing loss have been reported for more than a century, but it is only recently that the problem has been studied intensively. It has been suggested that even though people exposed to intense noise frequently experience a substantial noise-induced temporary threshold shift, sometimes accompanied by tinnitus (ringing in the ears), very often such symptoms seem to disappear within a short time. This may lead exposed persons to believe that no permanent damage has occurred. However, neither the (perceieved) loudness of a noise, nor the extent to which the noise causes discomfort, annoyance, or interference with human activity, are reliable indicators of its potential danger to the hearing mechanism. As there is considerable variation among individuals as to susceptibility, it is very difficult to identify a safe limit of noise exposure that can be applied for all persons. It has been shown that men and women are equally at risk of hearing damage, when exposed (J.L. Fletcher, 1972).

Most current knowledge of hearing loss due to noise has been obtained from industrial surveys. There is also evidence that nonindustrial exposure to noise can be harmful: nonoccupational activities and sources that might contribute to hearing loss include shooting, motorcycling, snowmobiling, music in concerts and cassette players with head-phones, toys, and fireworks (Fearn & Hanson, 1984; Axelsson & Jerson, 1985; Hellström & Axelsson, 1988; Ising, Babisch, Gandert, & Scheuermann,

1988; Dickinson & Hegley, 1989; Axelsson, 1991; Hellström, 1991; Kryter, 1991; Hellström, Dengerink, & Axelsson, 1992).

Results of several studies have confirmed that loud levels of music can produce considerable temporary threshold shift and even permanent threshold shift. Some researchers have found that hearing loss in musicians are not as large as suspected (J.D. Royster, L.H. Royster, & Killion, 1991). This is attributed, among other factors, to the frequent pauses, allowing some recovery, that characterize this kind of exposure (Axelsson & Lindgren, 1978).

7.1.2 Relation between Noise Exposure and Hearing Loss

Noise-induced hearing loss is of a sensory-neural type involving injury to the inner ear. In the normal auditory process, sound vibrations in the air travel through the ear canal and cause the eardrum to vibrate. The vibrations are then transmitted by the bones of the middle ear to the sensory organ of the inner ear (cochlea). Here they are transduced by hair cells into nerve impulses and transmitted to the brain, where they are perceived as sound (e.g., noise).

Blasts and other intense or explosive sounds can rupture the eardrum or cause immediate damage to the structures of the middle and inner ear, while hearing loss due to prolonged noise exposure is generally associated with destruction of the hair cells of the inner ear. The severity of noise-induced hearing loss depends on both the location and the extent of damage in the organ of Corti, which, in turn, depend on the intensity and frequency of the sound exposure. The higher the frequency, the nearer the point of maximum displacement of the basilar membrane is to the base of the cochlea where the basilar membrane is narrowest. This point is shifted towards the apex of the cochlea as the stimulus frequency decreases. The maximum stimulation of cells occurs at the point of maximum displacement. A large part of the upper cochlea is responsive to low frequency stimulation and loss of hair cells can be quite extensive without significant loss in low frequency sensitivity. On the other hand, much more localized and lower portions of the basal region of the cochlea are responsible for high frequency sound sensation and loss of hair cells in these lower portions results in significant losses of high frequency sensitivity (J.D. Miller, Rosthenberg, & Eldredge, 1971;

Hamernik, Ahroon, & Hsueh, 1991; see also Katz, 1994). The number of hair cells damaged or destroyed increases with increasing intensity and duration of noise and, in general, progressive loss of hair cells is accompanied by progressive loss of hearing.

The mechanisms involved in the destruction of the Corti organ are not completely clear, although numerous experiments have been performed with animals and several explanations been proposed. For example, mechanical stresses could destroy cells (Hamernik, Turrentine, Roberto, Salvi, & D. Henderson, 1984), noise may alter cochlear blood flow that in turn may alter the metabolic status of the cells and the local temperature leading to damaged proteins. Various theories have been reviewed by Ward (1973, 1991).

7.1.2.1 Laboratory studies

Laboratory studies of temporary and permanent hearing loss and of the anatomy of the noise-damaged inner ear have been carried out on a number of animal species. Temporary hearing loss studies on human subjects have included a variety of noise exposure patterns, including noises of different spectra, interrupted noise patterns, and short-duration noise exposures. In extrapolating the results of such studies to permanent hearing loss in man, it has always been necessary to consider: (a) temporary versus permanent threshold shift in man; (b) permanent threshold shifts in man versus animals; and (c) anatomical damage in animals versus permanent threshold shift in man.

Experimental studies have resulted in the following general observations (see W.W. Clark, 1991; Danielson, D. Henderson, Gratton, Bianchi, & Salvi, 1991): (a) There is considerable variability among individuals in susceptibility to temporary hearing loss, in the rate at which temporary hearing loss approaches its asymptotic level, and in the rate of recovery. (b) Temporary hearing losses in man are most pronounced at frequencies slightly above the predominant frequency of the noise stimulus. (c) In most cases, the rate of increase of temporary hearing loss (and subsequent recovery) is different for impulse noises and for steady noise. NITTS from impulse noise increases more rapidly than NITTS from steady noise (Ward, Selters, & Glorig, 1961) and recovery is slower (A. Cohen, Kylin, & LaBenz, 1966). (d) In general, the equal energy rule has been found to be compatible with experimental results for uninterrupted exposures to steady noise. However, it may not always be the best predictor of NITTS with regard to the audiometric frequency since it tends to overestimate NITTS below 2,000 Hz and underestimate losses above 2,000 Hz (Yamamoto, Shoji, & Takagi, 1968). Although NITTS from interrupted noise may be overestimated by the equal-energy rule (Ward, 1970), it is thought that the rule gives a good prediction of NIPTS from interrupted noise (Burns & D.W. Robinson, 1970). (e) Audiograms of persons exhibiting temporary hearing loss in laboratory studies tend to be similar to those of persons exposed to comparable noise over a period of several years (J.C. Nixon & Glorig, 1961). More recent studies in animal models are reviewed by Claric (1991).

7.1.2.2 Occupational hearing loss

Many articles have been published on the subject of occupational hearing loss (Atherley, Noble, & Sugden, 1967; Burns & D.W. Robinson, 1970; King, 1941; D.W. Robinson, 1971; Stone, Freeman, & Craig, 1971; Baughn, 1973; Burns, 1973; Passchier-Vermeer, 1974; Sulkowski, 1974; Bauer, Körpert, Neuberger, Raber, & Schwetz, 1991; see also Katz, 1994). All these studies were cross-sectional audiometric studies and many incorporated surveys of noise exposure. Specific occupational groups were usually studied, including workers in heavy industry, shipyards, textile plants, jet-cell test rooms, foundries, transportation, and forestry. Some definition of hearing impairment was generally applied in order to define a percentage of people with hearing loss. Audiograms were usually compared with so-called "normal" thresholds. In this respect, presbyacusis was often accounted for. In many cases, efforts were made to screen the

Figure 4. Percentage of workers with hearing impairment (average hearing loss at 1, 2, and 3 kHz >25 dB) [*From*: US National Institute for Occupational Safety and Health (Lampert & T.L. Henderson, 1973)].

data to exclude those persons who had previously held noisy jobs, possible nonoccupational noise exposures, and otological abnormalities. In some studies, such persons were purposely included in order to provide a realistic estimate of hearing levels in a typical noise-exposed population. Virtually every study revealed that workers exposed to intense noise daily, for several years, showed noise-induced hearing loss. Considerable hearing loss was rare at lower frequencies but frequent at higher frequencies.

In the studies for which noise exposure levels were known, a clear relationship was generally seen between increasing incidence of hearing loss and increasing noise level. In groups exhibiting considerable noise-induced hearing loss, the variation of audiometric thresholds was generally larger than in groups not exposed to noise.

Taking into account duration of exposure and age as well as other pathological conditions, Rey (1974) found that the proportion of workers with noise-induced deafness (defined as 25 dB average loss at 0.5, 1, and 2 kHz) was as high as 60 % in the metal industry (with sound pressure levels equal to and above 95 dBA). A. Cohen, Anticaglia, & H.H. Jones (1970) compared the mean hearing levels of exposed workers with those of a control group for several noise intensities and several durations of exposure and found that sound pressure levels between 85 and 88 dBA (or more) could be harmful to the ear. According to two other studies performed in industry, there is a definite risk of hearing damage associated with prolonged exposure to sound levels between 85 and 90 dBA, or more (Roth, 1970; Martin, Gibson, & Lockington, 1975).

Fig. 4 compares the percentages of workers with hearing impairment as a function of age for unexposed groups and for groups exposed to sound pressure levels of occupational noise of 85, 90, and 95 dBA (Lampert & T.L. Henderson, 1973). In this case, hearing impairment is defined as an average hearing loss greater than 25 dBA, at frequencies of 1, 2, and 3 kHz.

7.1.2.3 Factors that may influence the incidences of noise-induced permanent threshold shift

Certain people who live in remote and generally quiet areas of the world have been found to have unusually acute hearing in comparison with members of urban populations in corresponding age groups (S. Rosen, Bergman, Plester, El-Mofty, & Satti, 1962). However, it is not clear whether such audiometric differences are due to the lack of noise exposure alone. Differences in the patterns of hearing found between communities that are widely separated geographically and culturally may result from cultural, dietary, and genetic factors and differences in general environment (S. Rosen et al., 1962; S. Rosen & H.V. Rosen, 1971).

Although it has been suggested that older people are more susceptible to NIPTS (Kryter, 1960), there is no clear experimental evidence that this is so (Kup, 1965). Indeed, studies by Schneider, Mutchler, Hoyle, Ode, and Holder (1970) and H. Davis (1973) indicate that there is probably no causal relationship between age and susceptibility to NIPTS, at least in people of working age. More recently, there is some support for the observation that age and noise exposure can have a synergistic effect (Moscicki, Elkins, Baum, & McNamara, 1985).

There is some controversy in the literature as to whether pathological changes in the middle ear protect the inner ear from noise-induced damage, or whether they may instead increase the chance of noise-induced hearing loss. Some authors have expressed the view that in cases of middle ear damage, bone conduction becomes more effective and that the defense action of the middle ear muscles is impaired (Mounier-Kuhn, Gaillard, Martin, & Bonnefoy, 1960; Ward, 1962; Dieroff, 1964; Mills & Lilly, 1971). Conversely, others have reported cases where noise-induced hearing loss was less in damaged ears than in normal ears (G. Johansson, 1952).

Variation in individual susceptibility to noise-induced permanent hearing loss is illustrated by observations from surveys of occupational hearing loss, which indicate that workers from the same noisy environment display radically different audiograms, and that some workers, even after many years of exposure to noise, show little or no sign of noise-induced hearing loss.

Factors causing such differences in individual susceptibility could include fatigue of the acoustic reflex, anatomical differences in the structure of the middle and inner ear, the functional status of the autonomic system, and possibly latent vitamin B deficiency.

To some extent, the ear is protected from damage by the aural reflex. The contraction of the stapedius muscle changes the movement of stapes which increases the impedance of the conductive mechanisms. The amount of sound energy delivered to the inner ear is reduced by about 15-20 dB at low and middle frequencies (Møller, 1961). The effectiveness of the middle ear reflex as a protective device varies with the intensity and the spectrum of the sound. In normal ears, the onset of the reflex occurs at sound levels of 75-90 dBA. In man, the muscle contraction subsides very quickly after the onset of the sound for frequencies above 3,000 Hz, whereas for lower frequencies, the contraction can last for a considerable time (G. Johansson, Kylin, & Langfy, 1967). Impulsive sounds or sounds with a sudden onset can penetrate the ear without stimulating the protective mechanism, because of a time lag in the muscle contraction. Furthermore, the reflex action weakens with time and thus provides little protection against prolonged steady sounds. The fact that its effectiveness also varies considerably among individuals may be related to variations in individual sensitivity to certain sounds.

Measurements of NITTS have been used to investigate the protection provided by the stapedius reflex. In patients with peripheral facial palsy including unilateral stapedius muscle paralysis, the NITTS after low frequency noise exposure was significantly greater in the affected ear than in the unaffected ear (Zakrisson, 1975). However, results of animal studies, in which the stapedius muscle was severed, contradict these findings (Steffen, J.C. Nixon, & Glorig, 1963; Ferris, 1966).

7.1.2.4 Interaction of intensity and duration of noise exposure

Most data concerning the long-term hazard of noise are related to occupational exposure. There is a shortage of information about short-term exposures, and very little information concerning exposures lasting longer than 8 h per day. In order to predict the effects of long-term noise exposure, investigators have been obliged to extrapolate the results of field observations and laboratory investigations of NITTS. It is difficult to establish limits for safe noise exposure, since predictions using different methods of extrapolation conflict with each other.

The equal temporary effects rule is the hypothesis that the NIPTS due to long-term, daily, steady-state noise exposure is equal to the average NITTS produced by the same daily noise in healthy young ears (Ward, Glorig, & Sklar, 1958, 1959). In a later study, Ward (1960) suggested that metabolic insufficiency induced in the hearing organ by noise might underlie both the temporary and permanent hearing defects caused by excessive noise. NITTS studies also tend to support the observation re-

Figure 5. Percentage of exposed population that will incur no more than 5 dB NIPTS shown as a function of exposure level. Population ranked by decreasing ability to hear at 4,000 Hz. [US EPA, 1974b].

flected in industrial studies of NIPTS that for a given length of exposure, frequently interrupted noise is less harmful than continuous steady-state noise of the same equivalent level (Ward, Glorig, & Sklar, 1959; J.D. Miller, Watson, & Covell, 1963). An extension of this theory is that NIPTS is unlikely, if there is complete recovery from the NITTS before the beginning of the next day's exposure (Kryter, Ward, J.D. Miller, & Eldredge, 1966).

The equal energy rule is the theory that the hazard to hearing is determined by the total sound energy (the product of sound intensity and duration) entering the ear each day. This rule has natural appeal, since the exposure dose is quite simple to assess and, according to epidemiological data, is reasonably well correlated with the accumulated physical damage. The rule allows a 3-dB increase in a steady sound level for each halving of the duration (Burns & D.W. Robinson, 1970; Ward & D.A. Nelson, 1971; US EPA, 1974b; Martin, 1976). However, it should be noted that the range of sound duration covered by this rule might be limited by the need for protection against possible damage by high level, short duration, and impulsive sounds.

Various other theories are based, to a certain extent, on the equal temporary effect hypothesis. Such criteria are usually identified by the change in sound level that is necessary for each doubling of the exposure duration, for example, the "5-dB rule" means that the level must be

Table 2. Hearing loss criteria (Ishii, 1993a).

Source Average (kHz)*	Frequency (dB)	Fence
American Academy of Opthalmology and Otolaryngology** (1961)	0.5, 1, 2	25
American Academy of Otolaryngology*** (1990)	0.5, 1, 2, 3	25
National Institute of Occupational Safety and Health (Kryter, Williams, & D.M. Green, 1962; J.D. Harris, 1965)	1, 2, 3	25
Occupational Safety and Health Act (US Department of Labor, 1983)	2, 3, 4	10

** *AAOO and AMA (pre-1971) were the same.*
*** * *AAOO's hearing section separated to AAO (post-1979), AMA (post-1971), and ANS*

5 dB less for each doubling of the exposure duration. The rules most frequently quoted in the literature are:

(a) 3-dB rule: equal energy rule incorporated in the international standard issued by ISO 1999 (1990);

(b) 5-dB rule: purported to partially compensate for typical interruptions and intermittence and applied in the Walsh-Healey Public Contracts Act (1969) in the USA;

(c) 4-dB rule: purported to be more reliable for protection at higher frequencies than the 5 dB rule and used since 1973 by the United States Air Force (US Air Force, 1989); and

(d) 6-dB equal pressure rule, a more conservative criterion suggested by some research workers**.**

To simplify different damage risk criteria, noise exposure histories are frequently expressed as equivalent continuous 8-h levels. For example, using the equal energy (3-dB) rule, an exposure of 88 dBA for 4 h could be expressed as an 8-h equivalent level of 85 dBA (that is 88 dB LAeq,4h and 85 dB LAeq,8h, respectively).

7.1.2.5 Estimation of hearing impairment risk

The hearing loss that may result from noise exposure can be expressed in terms of probable NIPTS, or hearing impairment. Lifetime exposures to 90 dB LAeq is judged to cause clearly noise induced hearing loss, but as levels reduce below 90 dBA it becomes increasingly difficult to disentangle noise exposure from other causes such as aging. The chances of showing an effect at 80 dB LAeq that is statistically significant are very small, although some individuals probably are affected. The percentage of people who will suffer an NIPTS of 5 dB at the most sensitive frequency (4,000 Hz) may be defined as a function of an equivalent 8-h level (Fig. 5). From this diagram, an 8-h continuous equivalent level of 75 dBA might be identified as the limit for protection against significant NIPTS. "Damage-risk" has been defined as the percentage of a population with a given amount of hearing impairment, after corrections have been made for those persons who would "normally" incur losses from causes other than noise exposure (ISO 1999, 1990). Table 2 presents a compilation of hearing loss criteria adopted by various US organizations (Ishii, 1993a). It should be noted that these criteria give hearing handicap indices and not noise-induced hearing loss indices (Ishii, 1993b).

7.1.2.6 The importance of high-frequency hearing

It is common practice to assess hearing disability for compensation purposes, and even for prevention purposes, in terms of the ability to understand “everyday” speech. According to the international standard (ISO 1999, 1990), hearing disability begins with a 25 dB loss averaged over the frequencies 500, 1,000, and 2,000 Hz. However, speech energy at higher frequencies is important for speech intelligibility and music perception, when listening conditions are less than optimal (i.e., in background noise or when the speech is distorted in some way), (Kryter, Williams, & D.M. Green, 1962; J.D. Harris, 1965; Niemeyer, 1967; Acton, 1970; Ceypek & Kuzniarz, 1974; Aniansson, 1974; Abel, Krever, & Arlberti, 1990; King et al., 1992). Under good listening conditions, impaired hearing may not diminish speech intelligibility because of the redundancy (multiplicity of cues) of speech. This redundancy is reduced in noisy conditions or when the speech is muffled, the accent or the message is unfamiliar, or when these constraints occur in combination.

Considerable evidence exists that the distortions in loudness contribute to degraded speech understanding (Villchur, 1974). The markedly altered loudness-growth function in cochlear-impaired hearing is often overlooked in the assessment of noise exposure and hearing impairment (Hellman & Meiselman, 1990).

The use of a simple, unweighted average at 500, 1,000, and 2,000 Hz for assessing noise-induced hearing disability is restrictive because most hearing loss occurs at higher frequencies. Consequently, the frequencies 3,000 Hz and 4,000 Hz are included in damage-risk formulae by some countries.

7.1.3 Effects of Impulsive Noise

At present, most knowledge of hearing loss due to impulsive noise comes from studies of the effects of gunfire (see, e.g., Coles, Garinther, Hodge, & Rice, 1968) with some limited data on noise impact from industrial situations (Dieroff, 1961b, 1974; Ceypek & Kuzniarz, 1974). Important properties of impulsive noise exposure include the peak level, duration, rise and decay times, type of wave form, repetition rate, spectrum, and number of impulses (Vos, 1990; Rice, 1992; Buchta, 1993; Rice & Robinson, 1995).

The present state of knowledge is that a hazard exists and, accordingly, that ear protection should be worn when impulsive noises, measured with appropriate instrumentation, exceed a sound pressure level of 140 dB for more than 5 ms regardless of rise time, spectrum, or the presence of oscillatory transients. Higher maximum levels may be tolerable for durations of less than 5 ms. Sound pressure levels in excess of 165 dB even for short durations, are likely to cause acute cochlear damage (Acton, 1967; Burns & D.W. Robinson, 1970). It should be noted that the response time of the aural reflex is of the order of 100-300 ms, which is too long to give any protection against such short duration sound (Coles et al., 1968; Coles & Rice, 1970). Also the time constant “impulse” in sound level meters (35 ms) is too long for measuring peak levels of shorter duration than 5 ms. Therefore, unweigheted "peak" setting should be used.

Short impulses may harm the cochlea in spite of very short exposure times (microseconds, μs). Although the response time of the cochlea is about 1 ms, according to von Békésy's hydrodynamic theory of hearing, the shock waves of very short impulses of noise (a few μs) may be very effective on the base of the cochlea. Exposure to pure impulse noise may produce NIPTS mainly in the high frequencies and will not become demonstrated if the hearing threshold determination exclude testing at 4,000 Hz .

It is not common practice to extend the 8-h equivalent continuous sound pressure level criteria down to impulsive durations. Although Rice and Martin (1973) and Martin (1976) suggested that the criteria based on the equal energy rule may be applicable to high-intensity impulsive noise, this view has been questioned by results of more recent studies (Neuberger, Schwetz, Raber, Körpert, & Bauer, 1990; Schwetz, Raber, Neuberger, Körpert, & Bauer, 1992). Besides the single noise impulses at very high level (greater than L_{peak} = 130 dB), the impulse contents of industrial noise (e.g., noise in metal industry, see Dieroff, 1961b) may be important risk factors for hearing loss. Such noises may cause more hearing loss than noise without impulses when both have the same LAeq,8h. The higher risk is sometimes taken into account by impulse adjustments ("penalty" factor) of 2 to 8 dB. However, these values are uncertain.

Exposures to impulsive noise may be important in the development of "sociacusis", for example, due to excessive exposures to impulsive noise in do-it-yourself work in the home, in children's playing with noisy toys, and in use of fireworks. It is commonly believed that to avoid hearing deficits, performers and audience should not be exposed to more than 140 dB peak of impulsive sounds such as from toys and fireworks.

7.1.4 Infrasound and Ultrasound

Frequencies below 16 (or 20) Hz are referred to as infrasonic frequencies. Infrasound is audible. However, the human hearing has a very narrow dynamic range at infrasonic frequencies; the range from the first soft perception to pain is only 30-40 dB. Perception of sound from 100 Hz down to about 2 Hz is a mixture of auditory and tactile sensations. For example, frequencies around 10 Hz, can cause discomfort through a modulation of the vocal cords. But the main sensitive organ for sound at frequencies below 20 Hz is within the ear and not in the breast or stomach. There is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above detection threshold may cause perceptual effects but these are of the same character as for "normal" sounds.

Reactions caused by extremely intense levels of infrasound can resemble those of mild stress reaction and may include bizarre auditory sensations, describable as pulsation and flutter. Intense levels of infrasound can cause resonance responses in various organs in the human body, although long-term effects of such stimulation are not known. Effects of low-frequency noise (approximately <200 Hz) on hearing have been demonstrated as temporary threshold shifts at intense exposure levels and possibly with a longer recovery period than for higher pitch sounds (von Gierke & C.W. Nixon, 1976). At extreme pressure produced by very low-frequency noise, tympanic membrane damage may occur with some inner ear damage (von Gierke & C.W. Nixon, 1976).

The effects of high intensity ultrasound (above 20 kHz and sound pressure levels of 105 dB) are reported to be similar to those observed during stress. However, these effects may be partly due to associated high (but less than ultrasonic) frequency sound (Acton, 1967). It is usually believed that ultrasound pressure levels below 105 dB have no adverse effects.

7.1.5 Combined Effects

The adverse effects of noise on hearing may be enhanced by a variety of ototoxic drugs and environmental chemicals. Theoretically, the potentiation of noise-induced hearing loss by chemical agents may mean that noise exposures which would otherwise not disrupt hearing may become damaging due to the presence of such a co-factor. The practical significance of such interaction effects is difficult to assess due to the paucity of dose-effect curves in combined exposure studies. The interaction of noise and ototoxic drugs might be expected to be the most important in the case of community noise exposure. On the other hand, the interaction of ototoxic chemicals and noise is more likely to affect individuals in the work environment.

7.1.5.1 Noise and ototoxic drugs

The aminoglycoside antibiotics, cis-platin, loop diuretics, and salicylate represent therapeutic agents with significant ototoxic potential. The effects of such ototoxicants range from permanent auditory detection threshold elevation after exposure to aminoglycosides and cis-platin, to temporary impairment of threshold with the loop diuretics. Chronic, high-dose aspirin therapy most commonly produces reversible tinnitus rather than a primary disruption in auditory thresholds. Many studies have reported the potentiation of cochlear hair cell loss or of auditory threshold loss by the combined exposure of laboratory subjects to noise and aminoglycoside antibiotics (e.g., Vernon, J.J. Brown, Meikle, & Brummett, 1978; J.J. Brown, Brummett, Fox, & Bendrick, 1980; Dodson, Bannister, & Douek, 1982; Collins, 1988). Potentiation of dysfunction and cochlear damage has also been reported in animals co-administered the anti-tumor agent cis-platin and octave band noise at exposure levels of 85 dB continuously for periods of 5 days (Gratton, Salvi, Kamen, & Saunders, 1990).

The potentiation of impaired auditory function during aspirin therapy is less well established and conflicting findings have been reported. McFadden and Plattsmier (1983) reported evidence for potentiation of temporary hearing loss in human subjects exposed to noise if they had been treated with high doses (3.9 g over two days) of aspirin. Lower doses of aspirin did not appear to potentiate the noise-induced threshold shift. Laboratory investigations using animal models have reported inconsistent findings. Salvi, Boettcher, Spongr, and Bancroft (1991), for example, failed to demonstrate functional or structural differences in the cochlea between noise exposed chinchillas and subjects receiving combined exposure to salicylates and noise. Thus risk assessment for the enhanced temporary noise-induced hearing loss by aspirin is especially difficult. Similarly, there are no data available on the interactive effects of loop diuretics and noise.

7.1.5.2 Noise and ototoxic chemicals

Ototoxic chemicals include chemical asphyxiants, organic solvents, and metals. All of these agents are used in occupational settings, and some of the organic solvents are also used within households in glues, stain removers, and paints. Some organic solvents, notably toluene, are abused because of their psychopharmacological properties. A variety of chemical asphyxiants alone can disrupt auditory function in laboratory animals including carbon monoxide, cyanide (Konishi & Kelsey, 1968), and phypoxic phypoxia (Nuttall, 1984) under severe conditions. However, evidence shows that exposure to very high carbon monoxide levels can potentiate hearing loss in subjects exposed to noise simultaneously, and destroy outer hair cells in the cochlea (J.S. Young, Upchurch, Kaufman, & Fechter, 1987; Fechter, J.S. Young, & Carlisle, 1988). Supportive evidence is suggested by an epidemiological investigation on the combined effects of cigarette smoking and occupational noise exposure showing that noise-exposed smokers had an excess rate of hearing loss compared to non-smokers when the main effect of age was removed from the analysis (Prince & Matanoski, 1991). Carbon monoxide is one constituent of cigarette smoke and smokers do have elevated carboxyhemoglobin levels.

Several organic solvents are known to be ototoxic by themselves including toluene (Pryor, Dickinson, Howd, & Rebert, 1983; Sullivan, Rarey, & Conolly, 1989), styrene (Muijser, Hoogendijk, & Hooisma, 1988; Pryor, Rebert, & Howd, 1987), carbon disulfide (Sulkowski, 1979; Rebert, & Becker, 1986), n-butanol, and trichloroethylene (Velazquez, Escobar, & Almaraz, 1969). Non-occupational exposures occur to alcohol consumption (Wheeler, Dewolfe, & Rausch, 1980), to trichloroethylene which has been used as a dry cleaning agent, and to toluene primarily in glues and in spray paints. Chronic glue sniffing can produce profound hearing loss (Ehyai & Freemon, 1983). Studies designed to detect an ototoxic interaction between solvents and noise (e.g., Barregård & Axelsson, 1984) have found effects in some, but not in all instances. Hearing loss has been studied among factory workers exposed to noise and high levels of toluene (Morata, Dunn, Kretschmer, Lemasters, & Santos, 1991) or carbon disulfide (Morata, 1989). The results were that each of these solvents did produce greater hearing loss in combination with noise exposure than when presented alone. A.-C. Johnson, Juntunen, Nylen, Borg, and Höglund (1988) reported that rats exposed sequentially to toluene (1,000 ppm, 16 hours per day of 5 days per week for two weeks) and to noise (frequency modulated noise of 100 dB LAeq for 10 hours per day, seven days per week for four weeks) showed greater threshold elevation than did subjects exposed only to noise or to toluene. Fechter (1993) did not find a potentiation of noise-induced hearing loss among laboratory animals acutely exposed to high doses of styrene.

Adverse interactive effects with noise have also been demonstrated for heavy metals like lead, arsenic, and mercury (Haider, Kundi, Groll-Knapp, & Koller, 1990).

7.1.5.3 Other combined effects

Effects of combinations between noise and head injury and/or ear disease have been quantified in multivariate analyses by Neuberger, Körpert, Raber, Schwetz, and Bauer .(1992). Combined exposure to steady-state and impulse noise showed lower temporary threshold shifts than the same noises when presented alone. However, significant differences were found only at 30 min main exposure (Kundi, Weninger, Stidl, & Haider, 1984). The combination of high noise exposure and whole body vibration may lead to a significant aggravation of hearing losses (Manninen, 1990; 1993).

7.1.6 Auditory Effects of Community Noise

In a study performed by Moch-Sibony (1984), the auditory discrimination ability of similar sounding words under quiet testing conditions was evaluated by comparing children attending a noisy school near the Paris Airport and children in a sound-attenuated school. The children in the sound-attenuated school had better auditory discrimination scores than children matched by social class who attended the nearby unattenuated school. In a field study carried out by Tarnopolsky, Watkins and Hand (1980) acute as well as chronic tinnitus (ringing in ears) was frequently reported among subjects exposed to aircraft noise exceeding 45 NNI compared to subjects exposed to aircraft noise up to 45 NNI.

Considering the discrepant outcome of studies on auditory effects of community noise, it is difficult to draw definite conclusions on its possible adverse effects. However, relating the knowledge of auditory effects of noise exposure in general (e.g., community and occupational noise) to exposure levels of aircraft noise may, to some degree, facilitate a risk prediction. Calculated Ldn exposure levels in residential areas surrounding Scandinavian airports indicate that the most intense levels typically are between 65 and 75 dBA (Andersson & Lindvall, 1988). Comparing these exposure levels to the rekommendations in ISO 1999 (1990), which is based on equivalent continuous sound levels, one cannot conclude that there is a pronounced risk of hearing impairment.

When determining the risk of hearing impairment, it is important to consider the entire noise exposure (e.g., occupational, road traffic, aircraft noise, and noise from leisure activities). According to ISO (1990), there is no risk of acquiring a hearing impairment at an equivalent continuous sound level during 8-h work at 80 dBA. However, an additional exposure to, for example, aircraft noise during nonworking hours cannot be excluded from giving rise to a hearing impairment. That is, the ISO criterion is based on the assumption of a noise exposure of 40 h/week; the auditory system being assumed to recover during the nonworking hours of the week. Furthermore, it may be possible that exposure to aircraft noise can aggravate already existing hearing difficulties.

In military low-altitude flying areas (75-300 m above ground) the sound pressure level on ground may become 110-130 dB LAmax. One overflight noise event with a maximum sound pressure level of 130 dBA and a duration of 0.9 s contains the same energy as an 8-h exposure to 85 dBA. The steep level increase, however, of military low-altitude overflight noise may result in a further aggravation of the damaging potential. Noise-induced hearing threshold shifts may occur after such noise exposures in sensitive individuals as suggested by animal studies (Gehrig, Meyer, Ising, Kuhl, Schmidt, & Grützmacher, 1993) as well as epidemiological investigations (Ising, Curio, Otten, Rebentisch, & Schulte, 1993; Ising & Rebentisch, 1993a).

7.1.7 Summary

Hearing disability may be assessed in terms of difficulty in understanding acoustic signals and speech. The amount of loss at the speech frequencies has been used as a basis for monetary compensation and varies from one country to another. The unweighed average of the losses, in dB, at 500, 1,000 and 2,000 Hz, that is widely used for assessing noise-induced hearing impairment, is misleading. The reason for this is that noise-induced hearing deficits usually occur at 2,000 Hz and above and because the main frequencies involved in speech are 500 to 4,000 Hz. Commonly, the frequency of 3,000 Hz should also be included in damage assessment formulae. Frequencies of 4,000 and 6,000 Hz are of special interest in early detection of noise-induced hearing loss. In practice, very often the hearing loss of 500, 1,000, 2,000 and 4,000 Hz or 1,000, 2,000 and 4,000 Hz or 3,000 Hz only are used to assess the hearing deficits.

There is some disagreement concerning the relationship between the relative hearing-damaging capacity of the sound pressure level of noise and its duration. Therefore, to assess the noise-induced hearing-loss, the influence of sound pressure level and duration are taken into account, separately. However, the hypothesis that the hearing damage associated with a particular noise exposure is related to the total energy of the sound (i.e., the product of intensity and time) is used for practical purposes by calculating the noise load over a short time interval such as one or exceptionally a few days. Thus, from a hearing-deficit point of view, noise is primarily described in terms of equivalent continuous sound pressure level, LAeq, measured in dB. For occupational noise, the level is usually averaged over the entire 8-h shift (Leq,8h), and exceptionally over 40 h per week.

Available data show that there is considerable variation in human sensitivity with respect to hearing impairment. The hazardous nature of a noisy environment is, therefore, described in terms of “damage risk”. This may be expressed as the percentage of people exposed to that environment who are expected to suffer noise-induced hearing impairment after appropriate allowance has been made for hearing losses due to other causes, mainly aging. It is generally believed that this risk is negligible at noise exposure levels of less than 75 dB LAeq,8h, some would say below 80 dB LAeq,8h, but increases with increasing levels. The threshold value below which noise cannot damage hearing, may be even lower due to exposures combined with ototoxic drugs, chemicals, vibration and shiftwork.

It is not yet clear whether the damage risk rules can be extended to the very short durations of impulsive noise. Available evidence indicates that the risk increases when impulsive sound pressures reach 130-150 dB “peak” or when their noise immission level (NIL) exceeds 115 dB (Schwetz et al., 1992). The addition of impulsive noise on a steady noise may increase the risk for damage at 80-110 dB LAeq,8h and 100-130 dB peak. However, it is not yet clear to what extent impulsive noises and low-frequency noises should be given extra consideration in damage risk calculations.

7.2 Sensory Effects

7.2.1 Aural Pain

The threshold of pain for sound exposures in normal hearing persons is in the region of the sound pressure level of 110-130 dB, although there is a fairly wide range of individual variability especially for high frequency exposures (von Gierke, H. Davis, Eldredge, & Harry, 1953). The threshold for physical discomfort called loudness discomfort level (LDL) or uncomfortable loudness level (ULL) is in the region of 80-100 dB SPL (Spreng, 1975).

In abnormal hearing, for example, in cases of inflammation, pain may be caused in the eardrum or middle ear by sound pressure levels of about 80-90 dB. In many cases of sensorineural hearing disorders, such as Ménière’s disease, a symptom appears called dysacusis, which is a lowering of the threshold of aural discomfort and pain.

An important consideration with regard to aural pain is the effect of noise on hearing-aid users. Discomfort associated with exposure to sudden loud noises, loud music, and even raised voices is a common complaint of people who wear hearing aids. Hearing aids that automatically limit output to sound pressure levels of 100-120 dB or less, provide protection for sensitive ears, provided they are properly selected and fitted (Gabrielsson, B. Johansson, B. Johnsson, Lindblad, & L. Persson, 1974).

7.2.2 Other Sensory Effects

Tinnitus (ringing in the ears) is a common accompaniment of hearing impairment. It is sometimes defined as the illusory sensation of sound not brought about by simultaneously applied acoustical signals (Lutman & Haggard, 1983). Some forms of tinnitus are due to the sound produced by the blood flows through structures in the ear. Commonly, tinnitus is referred to as sounds that are emitted by the inner ear itself and are heard by the subject, physiological tinnitus. A sensitive microphone may pick up the sounds heard by the subjects in some cases. However, most forms of tinnitus are not accompanied by otoacoustic emissions.

Certain sensorineural disorders, and most frequently noise-induced hearing losses, are accompanied by abnormal loudness perception which is known as loudness recruitment. The absolute hearing threshold may be elevated and the rate of growth of loudness with sound intensity is more rapid than normal. The shape of the psychophysical function may vary considerably between individuals with recruitment (Hallpike & Hood, 1959; Hallpike, 1967). The phenomenon of recruitment is common in noise-induced hearing loss.

Some sounds may be perceived distorted. This is called paracusis. For example, a tone is heard but the pitch of the tone is inappropriate. Such paracusis only occurs in conjunction with a considerable loss of auditory sensitivity.

7.2.3 Summary

Physical ear discomfort of noise exposure starts from sound pressure levels of 80-100 dB and up. Persons with some ear or sensorineural hearing disorders and hearing-aid users may experience aural pain on exposure at even lower levels. Tinnitus and loudness recruitment are common sensory effects accompanying temporary or permanent hearing impairment. Both phenomena may be experienced as the result of exposure to very loud music.

7.3 Perception of Noise

Whether a sound is classified as noise depends in part on the quality of the auditory experience (perception) it produces. The acoustical engineer might prefer to classify kinds of sounds according to physical terminology such as white noise, pink noise or tones, but most people prefer to classify sounds according to perceptual quality; we label them music, community noise, speech, etc (e.g., Handel, 1989). Due to lack of knowledge about the adequate classification system for community noise, the responsible bodies in the industrialized countries have written different regulations for specific noises, that is, for road traffic noise, aircraft noise, impulsive noise, etc. This development is governed by practical necessity rather than scientific knowledge.

It would be desirable to have a model that would relate auditory experience to physical measurement of sound as well as having another model which would in turn relate the quality of the auditory experience to the annoyance produced by community noises. Unfortunately, our knowledge is not extensive enough to allow the development of general models, but some specific models have been applied to certain conditions.

The requirements for a general model would be extensive indeed. Not only would variables related to the physical features of the noise be required, but also variables pertaining to the listener's attitudes and present activities. Physically identical sound may become noise to one person and music to another, depending on whether one likes Mozart or rock and roll. The same noise may also be pleasant at midday but annoying at midnight. The noise of the neighbor's lawnmover may be annoying if (s)he mowed the lawn two days ago, but a pleasant relief if (s)he just returned from a six week vacation to clean up an overgrown front yard. Attitude is a major factor in annoyance (Job, 1988a; Fields, 1993b).

7.3.1 Perceived Noisiness and Annoyance

It has been proposed that another dimension of human response to noise, perceived noisiness, is similar to, but distinct from loudness, and that perceived noisiness may be a better predictor than loudness of the adverse reactions to sound (e.g., Kryter, 1970, pp. 270-277). However, the term "noisiness" does not have a unique meaning; it may refer to unwanted sound or to a specific sound quality. Two sounds of equal loudness need not be equally noisy. The difference between loudness and noisiness in terms of spectral content is small for broad-band sounds but becomes important when the sound has an irregular time and frequency structure. Research in noise perception has shown that people can differentiate concepts such as loudness, perceived noisiness and annoyance but only when the concepts are carefully defined (B. Berglund, U. Berglund, & Lindvall, 1975a, 1976; Hellman, 1982).

Community noise perception actually involves perception of several sources at the same time. Experiments have shown that observers can identify and assess a specific noise source in a mixture of sounds. Such a source may contribute more to annoyance than can be estimated from total loudness or sound pressure level (U. Berglund, 1981; B. Berglund, U. Berglund, & Lindvall, 1980). Loudness or annoyance summation of combined noise sources allows one to predict total loudness according to the

”loudest component” (B. Berglund, U. Berglund, Goldstein, & Lindvall, 1981). This does not necessarily hold for a mixture of noise and strong tonal components. More complex models have been successfully tried (Powell, 1978, 1979; Ollerhead, 1980; B. Berglund et al., 1981; Hellman, 1982) but all point to the same important principle, namely the effects of masking and mutual inhibition.

At present the continuous energy equivalent noise level is widely used as an index for describing community noise. This index may be useful when comparing similar noise situations (same dominant noise sources, broad-band noise spectrum without discontinuities, etc.). However, numerous authors (e.g., Gjestland & Oftedal, 1980; Fields & Walker, 1982) have shown that the equivalent level is not applicable when comparing noise situations of unequal character, for instance road traffic noise vs. rail noise, continuous vs. intermittent traffic. Impulsive noise, in particular, produces more annoyance for the same continuous energy equivalent noise level than does non-impulsive noise (Job, 1988a; Bullen, Hede, & Job, 1991).

It is important to establish indices based on physical measurements which correspond to the perceptual qualities of different noise situations. However, these qualities are functions also of a set of personal and psychological factors such as expectation, habituation, attitude, and social activity. Consequently, for health assessments we will probably need a number of noise indices based on different physical pa-rameters, each one designed for a specific purpose: for example, an index for sleep disturbance should probably be based on maximum sound levels and number of events, whereas the time distribution of noise events above a certain level may be the most significant parameter for speech interference.

From a perceptual point of view important physical parameters for describing community noise are sound pressure level (instantaneous, maximum, equivalent) or sound pressure level distribution, frequency spectrum (weighting functions, tonal components), single noise events (number and time distribution), variations (rise time, levels, spectrum of amplitude variations), familiarity, and predictability.

7.3.2 Methods for Measuring Perceptual Attributes of Sounds

Various procedures have been used to evaluate people’s responses to noise other than by scaling loudness as discussed above. Research has shown that annoyance and other such perceptual attributes also can be scaled by direct ratio scaling methods (e.g., Hellman & Zwislocki, 1961; B. Berglund, U. Berglund, & Lindvall, 1975a, 1976, 1986a; Zwislocki & Goodman, 1980). Some versions of these methods have become known as absolute methods, that is, absolute magnitude estimation and absolute magnitude production.

In addition to ratio scales of loudness discussed above (Stevens, 1975; Marks, 1974), these absolute scales are expected to provide not only the slope of the functions but also the absolute perceptual scale values. Because individuals use the same subjective units for different perceptual variables, typically equality of assigned numbers successfully predicts equality of perceptual magnitudes in laboratory settings (e.g., Hellman, 1976; Hellman & Zwislocki, 1968).

More generally, this absolute scaling approach enables us to compare different physical events in terms of one perceptual attribute or different perceptual attributes of the same event. The method has become gradually more refined with time and provides stable results in the laboratory. Because the method has proven applicable to a large number of diverse perceptual variables, it is likely to be useful in the evaluation of perceptual responses to community noise. Explicit rules for the application of the method are available (Zwislocki & Goodman, 1980; Zwislocki, 1983). If field tests of the method give positive results, investigation of people's self-reports to community noise could be greatly simplified and unified.

One of the central problems in assessing the perception of community noise sources is that different persons may be required to make judgment of different sources, widely separated in time and space. This makes it dubious to compare judgments across conditions because it is clear that individual differences exist in people's perception of sound. One way to deal with this problem is to construct a ”master scale” that can be used as a common reference of all judgments of noise sources independent of the judgment peculiarities of individual subject groups. Such a scale provides a defined unit of measurement of the attribute. When applied to a psychophysical problem, the target community noise can be expressed in terms of the perceptual or physical units of the master function (B. Berglund; Berglund, U. Berglund, & Lindberg, 1983; B. Berglund, U. Berglund, & Lindvall, 1986a; B. Berglund, 1991).

7.3.3 Summary

There is no general model that relates physical measures of sound to auditory experiences (e.g., loudness) and, in turn, to annoyance (or noisiness) of community noises. The difference between loudness and noisiness in spectral content is small for broad-band sounds but increases when the time and spectrum involves several sources at the same time. Due to effects of masking and inhibition, total loudness of combined noise sources may be predicted roughly by the ”loudest component”. A number of noise indices are needed based on physical parameters which correspond to the perception of different noise situations. Perceptually important physical parameters are: sound level, sound level distribution, frequency spectrum, single noise events, variations, familiarity, and predictability.

Direct scaling methods can be used not only for measuring loudness but also annoyance and other perceptual attributes. To make judgments of noise sources independent of the judgment peculiarities of individual subject groups, the scale used should provide a defined unit of measurement of the attribute (e.g., by a Master Scale).

7.4 Interference with Speech Communication

7.4.1 Voice Communication

The primary method of communication between humans is speech. Speech signals consists of rapid fluctuations in pressure generated by the voice. These sounds are radiated into the air, detected by the ear and assessed by the brain. The radiated acoustic energy spreads spatially and diminishes rapidly in intensity (Flanagan, 1972). However, air can support only limited variations in pressure without distorting the signal. The acoustic and the physiological noises of the body set limits to the sensitivity of the receiving ear.

The capacity of the human auditory channel is much determined by the ability of the receiver to discriminate differences in the received signal. Another is the ability of human beings to assimilate and process information.

Speech is the result of a motor behavior which is learned. It is controlled by feedback of the hearing mechanism and the speech musculature coordinated by the central nervous system. In noisy environments, voice levels tend to be raised (Pearsons, Benett, & Fidell, 1976; Lazarus, 1990), possibly resulting in vocal cord stress and then voice disorders (von Klingholz, Siegert, Schleier, & Thamm,, 1978). In speech, cues are being found between 100 and 8,000 Hz. Most of the acoustical energy of speech falls between 100 and 6,000 Hz, the most important cue-bearing energy between 300 and 3,000 Hz. Speech contains much extra information that is unnecessary for comprehension. Speech can be understood even when some cues are missing.

To be informative, a spoken language must consist of a finite number of distinguishable, mutually exclusive sounds (Flanagan, 1972). The basic linguistic elements are called phonemes. They may be looked upon as a code uniquely related to the articulatory gestures of a given language. In addition to phonemes, the temporal features of speech such as variations in stress (loudness) and pitch (melody) and rythm constitute the prosody of speech giving the temporal pattern in which the phonemes are embedded. Parallel to phoneme discrimination, the study of speech rhythms (prosody) is a requirement for assessing correctly speech perception. For a constant signal to noise ratio, speech spoken loudly is more difficult to understand than when spoken softly (Rostolland, 1982, 1985; Lazarus, 1990).

7.4.2 Perception of Speech

Auditory psychophysics (psychoacoustics) deals principally with the abilities and limitations of the hearing system as a transducer of all acoustical signals. However, speech is a multidimensional signal that elicits a linguistic association which is mainly based on the identification and classification of auditory patterns. A perceptual categorization takes place involving a breakdown of the signal into discrete message elements (Handel, 1989). In addition to auditory discrimination, acoustic cues are needed to comprehend the simple speech elements, like phonemes.

The threshold for detecting a difference in the pitch of two successively presented pure tone frequencies may be as small as one part in one thousand (Rosenblith & K.N. Stevens, 1953). The threshold for detecting a difference in intensity may be less than 1 dB (Riesz, 1928; Houtsma, Durlach & Braida, 1980; Green, 1995). It has been estimated that the normal listener can distinguish about 350,000 different tones using the procedure with two successively presented tone frequencies (S.S. Stevens & H. Davis, 1938). It is more difficult for humans to identify and label sounds presented in isolation. When equally loud pure tones are presented individually for absolute judgment of pitch, most listeners are able to accomplish perfect identification among only five different tones (Pollack, 1952). In comparison, people with absolute pitch may identify more than 50 frequencies. It is clear that absolute and differential discriminations yield substantially different estimates of the informational capacity in humans (Flanagan, 1972).

A general principle of auditory perception is the so-called phonemic restoration by noise for missing speech sounds. Speech interrupted with interpolated noise may be perceived more complete and continuous than the same speech segments combined with silent gaps (G.A. Miller & Licklider, 1950; R.M. Warren, 1970; Bergman, 1980). Speech interrupted with silent gaps may be perceived more annoying than speech interrupted by superimposed noise (Preis & Terhardt, 1989; B. Berglund, Harder, & Preis, 1994). However, as stated by Moore (1982), the phenomenon of perceptual filling in of missing sounds will occur only when one source is perceived as masking or blocking another. Repp (1992) suggests that the apparent auditory restoration that accompanies phonemic restoration is illusory and does not interact with auditory processing.

7.4.3 Masking and Intelligibility

The interference of noise with speech communication is a masking process in which simultaneous noise renders speech unextractable. The ratio of a given desired signal level (speech, music) to that of the interfering noise will determine to what extent the signal can be perceived. The more intense the level of the masking noise and the more energy it contains at speech frequencies, the greater will be the percentage of speech sounds that are undiscernible to the listener.

An important aspect of communication interference in occupational situations is that failure of workers to hear warning signals or shouts may lead to injury. Although cases do not appear to have been documented in the literature, there is anecdotal evidence of such occurrences.

In the last half century, knowledge concerning the masking of simple signals such as pure tones, narrow bands of noise, and even isolated phonemes of speech has increased considerably. Empirical relationships are available that permit accurate prediction of the audibility for a normal-hearing listener of a particular speech sound in the presence of a specified noise (Webster, 1969, 1974; Kryter, 1985, 1994). However, communication is almost never carried on by means of single acoustic signals, but rather by a rapid sequence of different speech sounds, the overall intensity and spectral distribution of which are constantly shifting; in fact, the same word, when repeated, may be quite different acoustically. Furthermore, even when the masking noise is judged to be steady, the energy in different frequency regions fluctuates from moment to moment.

Most of the sentences of ordinary discourse can be understood fairly well, even when a large number of individual speech sounds are masked, because of the redundancy of speech. Even when a particular sound is masked or even omitted, the word or sentence in which it occurs may be correctly assessed because the remaining sounds are sufficient to convey the meaning. However, the interpretation required to compensate for the masking effect is an additional strain on the listener.

Other characteristics of the communication process affect the effectiveness of information retrieval, when masking and disturbing sounds are present. Examples of such factors are the familiarity of the listener with the language dialect or accent of the speaker, the importance and familiarity of the message, the presence of reverberation, the distance from speaker to listener, speech rate, the motivation and attention of the listener, and any hearing loss that may produce a degradation in the perceived sound. Thus, the relationship between the spectrum, level, and temporal characteristics of a masking noise and the "intelligibility" of ordinary speech, that is, the proportion of speech correctly understood, is very complex. Much research has involved the measurement of intelligibility of nonsense syllables and of isolated words in phonetically-balanced lists. Based upon work with real sentences, conversion charts have been constructed to transform scores involving only words to approximate expected scores for sentences of ordinary speech. For example, when 75 % of the items on a list of isolated words are correctly perceived, about 95 % of the key words in a sentence of ordinary discourse will be correctly heard (Kryter, 1970, 1994). Sentence intelligibility refers to the percentage of key words that are perceived correctly in a series of sentences.

7.4.4 Speech Interference Indices

Many attempts have been made to develop a single index based on the characteristics of the masking noise that directly indicates the degree of interference with speech perception. Naturally, such indices involve considerable degrees of approximation. The three most common indices are:

the articulation index (AI), speech interference level (SIL), and the A-weighted sound pressure level.

7.4.4.1 Articulation index

The articulation index (AI; French & Steinberg, 1947; Kryter, 1962) is the most complicated of these indices, since it takes into account the fact that some frequencies are more effective than others in masking speech. Frequencies below 250 Hz and above 7,000 Hz are not included, as they are not considered to contribute to the intelligibility of speech. The frequency range from 250 to 7,000 Hz is divided into 20 bands, each of which contributes 5 % to the total intelligibility. In order to determine the AI for a particular noise, the difference in dB between the average speech level and the average noise level in each of these 20 bands is calculated, and the resultant numbers are combined to give a single index. Essentially, this process predicts how much masking of individual speech sounds will occur and then integrates this information.

Although the AI is an accurate index for the prediction of the effects of noise on speech intelligibility, it is complicated to use and difficult for the layman to interpret. Thus, simplified procedures for estimating the AI from weighted measurements of octave-band levels have been developed (Kryter, 1962)

7.4.4.2 Speech interference level

The speech interference level (SIL) was designed as a simplified substitute for the AI (Beranek, 1947). Contributions to intelligibility by the lowest and highest frequencies have been omitted to a greater extent than for the AI. A modern version of the SIL is the arithmetic average of the sound pressure levels in the three octave bands centered at the preferred frequencies 500, 1,000, and 2,000 Hz (abbreviated SIL 0.5, 1, and 2). Many variations of SIL in terms of the specific octave bands to be averaged have been suggested. For example, SIL (0.25, 0.5, 1, 2) includes the 250 Hz band. At present, the US National Standards Institute and ISO (ISO TR3352, 1974, ISO 9921, 1988) recommend SIL (0.5, 1, 2, 4) as providing the best estimate of the masking ability of a noise.

Figure 6. Maximum distances outdoors over which conversation is considered to be satisfactory intelligible in steady noise (U.S. EPA, 1974b).

7.4.4.3 A-weighted sound pressure level as an index of speech interference

The simple A-weighted sound pressure level is also a useful index of speech interference. The A-weighting process emphasizes the middle frequencies, as do the AI and SIL, but does not omit the lowest and highest frequencies completely.

Experiments have shown that the AI is more accurate than any of the SILs or the A-weighted spund pressure level in predicting the speech-masking ability of a large variety of noises. For noises of practical importance, however, A-weighted sound pressure level and SIL continue to be used, as the advantage of accuracy in the AI does not outweigh the ease of measurement of the first-mentioned two indices. Comparisons of SILs and A-weighted sound pressure levels show that, on average, the SIL is about 8 dB lower than the A-weighted sound pressure level for the same degree of interference (Klump & Webster, 1963; Kryter, 1970; Lazarus, 1986, 1987), although for unusual noises the average difference might vary substantially.

7.4.5 Speech Communication Outdoors

Measurements indicate that, during relaxed conversation in the home, the speech level is approximately 55 dBA (Kryter, 1970; Pearsons, Benett ,& Fidell, 1976), and that as the noise levels increase, people tend to raise their voices to overcome the masking effect. The so-called "normal effort" voice resembles a "stage" voice, and is used when people are given a prepared text to read (Korn, 1954), or when they wish to project their voices. Since everyday speech is spoken at a reasonably predictable level, it is possible to express many of the empirical relationships between background noise level and speech intelligibility in a single graph, as in Fig. 6 (U.S. EPA, 1974). The data in this figure, which is applicable to outdoor conditions, is based on the assumptions and empirical observations that:

(a) at a distance of 1 m from the speaker, relaxed conversation occurs at a voice level of approximately 54-56 dBA and normal and raised voices at levels of approximately 60 and 66 dBA; and

(b) for 100 % sentence intelligibility the speech level should exceed the noise level by 15-18 dBA (see ISO 9921, 1988; Lazarus, 1990).

When the speech level is equal to the noise level, intelligibility falls to 95 %. Because of the redundancy of speech, 95 % intelligibility usually permits reliable although not necessarily comfortable conversation. The location of the curves in Fig. 6 may shift in certain circumstances, although it is difficult to predict to what extent spatial factors may facilitate or impair speech communication in noise. Lower noise levels may be required, if the speaker does not enunciate clearly or if the speaker and the listener use different dialects, or if 100 % discrimination of low-redundant words is required (foreign language, names, non-frequent words, and terminology). People with hearing impairment need more favorable speech-to–noise ratios depending on the variation of speech-to-noise ratio with frequency (Plomp, 1986).

Adequate communication in more intense levels of noise than those indicated in Fig. 6 can occur, if the messages are restricted, for example, when only numbers are being transmitted. Lip-reading or observing facial or manual gestures may also improve communication. If the noise source is clearly localized at a position different from that of the speaker, speech communication may be possible in more intense sound levels than those indicated in Fig. 6.

Intermittent and impulsive noises as well as noises fluctuating in level will provide various degrees of masking. Again, the redundancy of speech means that an isolated short burst of noise is unlikely to produce much disruption in the communication process; however, the likelihood of disruption increases with increasing duration and frequency of occurrence of the noise bursts.

Figure 7. Normal voice intelligibility as a function of the steady background sound level in a typical living room (U.S. EPA, 1974b).

The detailed characteristics of noises are also important. While the A-weighted sound pressure level is an adequate index of the speech-interfering quality of many noises, others may require a more detailed analysis. This is true of noises that are dominated by either low or high frequencies, for example, the rumble of distant traffic or the hiss of compressed air. For unusual noises, the AI should be calculated for a reliable prediction of speech intelligibility.

7.4.6 Speech Communication Indoors

The relationships shown in Fig. 6 apply only to outdoor (free field) communications, as they depend on the applicability of the inverse square law. Relationships indoors are different because of reverberations caused by reflections from the walls, floor, ceiling, and objects in a room. Instead of decreasing 6 dB for each doubling of distance, the sound level of the speech or the noise may drop by only 1 or 2 dB. There is no simple formula that will predict speech interference indoors. Therefore, Fig. 6 is used to determine the permissible noise level at specific distance up to 2 m, and to estimate this up to 8 m if the reverberation time is lower than 2 s. But it is also usual to set standards on the basis of the average sound levels of noise that have been judged in the past to be acceptable in similar settings.

For example, Fig. 7 (U.S. EPA, 1974b) shows the estimated sentence intelligibility, at speaker-listener distances greater than 1 m, as a function of A-weighted sound pressure level in the reverberant conditions found in a typical living room. This shows that for 100 % intelligibility, which is considered desirable for indoor listening conditions, a background noise level of less than 45 dBA is required.

A model for evaluating speech communication indoors taking background noise and reverberation into account is the Speech Transmission Index (STI) proposed by Houtgast (1980). The model employs a modulation transfer function (MTF), which quantifies the extent to which intensity fluctuations of speech are preserved in conditions of masking noise and reverberation from the speaker to the listener. The index is a single value from zero to 1.00 and correlates well with speech discrimination in different indoor conditions and languages (Houtgast & Steeneken, 1983; Humes, Dirks, Bell, Ahlstrom, & Kincaid, 1986). A simplified version called Rapid Speech Transmission Index (RASTI), in which a reduced number of octave bands are measured, is available in an instrument conforming to IEC Publication 268-/6 (1988).

7.4.7 Relevance for People with Hearing Deficits/Dysfunctions

Hearing impairment is accompanied by a loss of frequency resolution for some people. This causes a diminished ability to identify acoustical patterns underlying articulatory distinctions and, thus, extract information. Hearing impaired listeners require an increase in the minimum frequency separation between two spectral peaks, for them to have distinct auditory representations (Bailey, 1983). This has implications for discrimination of non-speech timbre, the phonetic quality of speech sounds and the strength of pitch sensations.

A number of speech perception errors are characteristic of hearing impairment. Perceptual confusion is affected by a number of acoustical features of the speech stimuli: consonant confusion, articulation features involving spectral contrasts, and voicing and nasality features depending much on temporal resolution.

The masking effect of noise in speech discrimination is more pronounced in the hearing impaired than in persons with normal hearing, particularly against a noise background of speech or babble (Hygge, Rönnberg, Larsby, & Arlinger, 1992). This may also be the case for the elderly (Bergman, 1980; Duquesnoy, 1983) and for children in the process of language acquisition (Nabelek & P.K. Robinson, 1982). This difference may reach as much as 10 dB and requires more favorable signal-to-noise ratio for the corresponding percentage of correct speech discrimination. This may be due to the widening of the critical band in sensorineural hearing disorders. If the listener is unfamiliar with the language spoken (e.g., children and second-language persons), a 5 to 10 dB larger signal-to-noise ratio is needed for acceptable speech intelligibility. In addition, the combined effect of noise and reverberation is also more pronounced for the hearing impaired. With aging even minor degrees of high frequency hearing impairment deteriorate speech discrimination in noise. Noise interference with speech discrimination results, therefore, in a great proportion of person disabilities and handicaps such as problems with concentration, fatigue, uncertainty and lack of self-confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of reactions to stress.

7.4.8 Summary

Noise interference with speech discrimination results in a great proportion of person disabilities and handicaps such as problems with concentration, fatigue, uncertainty and lack of self-confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of reactions to stress.

Most of the acoustical energy of speech falls between 100 and 6,000 Hz, the most important cue-bearing energy between 300 and 3,000 Hz. The interference of noise with speech communication is a masking process in which simultaneous noise renders speech unextractable. The ratio of a given desired signal level (speech, music) to that of the interfering noise will determine to what extent the signal can be perceived. The higher the level of the masking noise and the more energy it contains at speech frequencies, the greater will be the percentage of speech sounds that are undiscernible to the listener.

Measurements indicate that, during relaxed conversation in the home, the speech level is approximately 55 dBA. As the sound pressure levels of the noise increase, people tend to raise their voices to overcome the masking effect. Intermittent and impulsive noises as well as noises fluctuating in level will provide various degrees of masking.

The masking effect of noise in speech discrimination is more pronounced in the hearing impaired than in persons with normal hearing. This may also be the case for the elderly and for children in the process of language acquisition. This difference may reach as much as 10 dB and requires more favorable signal-to-noise ratio.

Although the articulation index (AI) is an accurate index for the prediction of the effects of noise on speech intelligibility outdoors, it is complicated to use and difficult for the layman to interpret. For noises of practical importance, however, the simple A-weighted sound pressure level is also a useful index of speech interference. There is no simple formula that will predict speech interference indoors.

7.5 Sleep Disturbance Effects

7.5.1 Nature of Sleep and Sleep Disturbance

Many people experience sleep disturbance due to noise and the problem has been reviewed by several authors (see, e.g., Griefahn, Jansen, & Klosterkötter, 1976; Vallet, 1987; Öhrström, 1993a). Social survey data indicate that sleep disturbance is considered to be a major environmental noise effect (Alexandre, 1974; Lambert & Vallet, 1994), even though there are 10-20 % sleep disturbance due to other reasons than noise (Langdon & Buller, 1977).

Exposure to noise can induce disturbances of sleep in terms of difficulty to fall asleep, alterations of sleep pattern or depth, and awakenings (e.g., Eberhardt, 1987; Griefahn, 1989, 1990). These effects are referred to as primary sleep disturbance effects. Recordings of sleep can be obtained by measuring the electrical activity of the brain (electroencephalogram, EEG), together with the electrical activity in the eyes (electroocculogram, EOG) and with the electrical activity in the muscles (electromyogram, EMG).

Other primary physiological effects that can be induced by noise during sleep are vegetative reactions such as increased blood pressure (Muzet & Ehrhart, 1980), increased heart rate (Öhrström, 1989), increased finger pulse amplitude, vasoconstriction, and change in respiration and cardiac arrhythmia (Carter & Hunyor, 1991), as well as body movements (Muzet, Naitoh, L.C. Johnson, & Townsend, 1974).

Exposure to nighttime noise can also induce secondary effects or aftereffects, that is, effects that can be measured in the morning or the day after the noise exposure. These secondary effects include reduced perceived sleep quality, increased fatigue, decreased mood or wellbeing and decreased performance (Öhrström, 1982). Long-term effects on psychosocial wellbeing have also been related to noise exposure during the night (Öhrström, 1989). The annoyance during night time influences the total daily annoyance level (Lambert, Simonnet, & Vallet, 1984).

The correlation between outdoor noise levels and sleep disturbance may be low, for example, because the higher the outdoor noise levels, the more the windows are closed (cf. Fidell & G. Jones, 1975; cf. Globus, Friedmann, H. Cohen, Pearsons, & Fidell, 1974). It is not clear in what proportion noise contributes to regularly occurring sleep disturbances or awakenings in the general population. The time needed to fall asleep, as well as the number of awakenings during the night and the feeling of tiredness in the morning influence the perceived sleep quality (Lukas, 1977; Öhrström, 1982).

Detailed laboratory studies of the problem have been made by monitoring EEG responses and changes in neurovegetative reactions during sleep. Several stages of sleep can be identified from EEG responses. On relaxing, prior to sleep, the EEG pattern changes from rapid, irregular waves to a regular pattern; the alpha rhythm. This is followed by sleep stage 1, characterized by prolonged reductions in wave amplitude and frequency. Later, in sleep stage 2, the pattern changes to one of bursts of waves (spindle waves) mixed with single, slow waves of relatively large amplitude (K-complexes). About 30-45 min later, periods of slow, high amplitude waves (delta waves) appear in the EEG (stage 3). When the delta waves occur for about 50 % of the recording period, the deepest sleep, stage 4, is reached. About an hour and a quarter later, the EEG pattern resembles that found in stage 1, but electrodes placed near the eye reveal joint rapid eye movements (REM); this is called stage 1–REM sleep during which most dreaming occurs whereas stages 1-4 often is referred to as non-REM sleep.

During normal sleep, a person progresses through sleep stages 1-4 with occasional reversals. The time spent in deep sleep and in the lighter stages of sleep depends upon age and there are also large differences between individuals. However, with increasing age, a greater proportion of time is spent in the lighter sleep stages and sleep length is typically decreasing; from the age of 60 years onwards, sleep stage 4 and also REM sleep is almost totally absent. It is believed that brain activation of REM sleep contributes to the development and maintenance of sensorimotor competence and its decline with aging is the result of brain maturation. Sleep is also a necessary prerequisite for good physiological and mental health (Hobson, 1989).

Stimulation by noise exposure causes changes in the EEG pattern lasting for a few seconds or more. These may appear as K-complexes (increases of wave frequency) that are only detectable by close inspection of the EEG recording, or as changes of sleep stage. It has been reported that the effects of noise are related to the stage of sleep. Results from some studies suggest that thresholds for awakening are lower in the REM sleep stage for nonimpulsive as well as impulsive noises (Berry & Thiessen, 1970). EEG pattern changes are least likely to occur in the REM stage (Thiessen, 1972).

As will be presented in the following, several noise factors influence sleep: level, fluctuations, number of exposures, type, time and informational content. Also individual factors are important for the effect of noise on sleep. Variables such as illness, age, sensitivity to noise, and irregular sleeping hours play a significant role.

7.5.2 Effects of Noise on Time to Fall Asleep

Difficulties to fall asleep due to community noise exposure may show up among the exposed persons in different ways. It may affect sleep latency, the need for using sleeping pills or ear plugs, and more precisely the time to fall asleep.

The time required to fall asleep is thus considered as an important aspect of noise-induced sleep disturbances. A longer time to fall asleep was found in sensitive as well as nonsensitive adults at sound pressure levels of 50 and 60 dB LAmax road traffic noise (Öhrström & Rylander, 1990). A reduction in the time needed to fall asleep was found among children who slept in a more quiet room (Eberhardt, 1987) and among adults who slept with closed windows as compared to sleeping with open windows (Griefahn & Gros, 1983). The number of noise events per time unit rather than the absolute noise level seems to be important for the time needed to fall asleep since the effects were similar at 45, 50, and 60 dBA of road traffic noise (Öhrström & Rylander, 1990, Öhrström, 1991).

7.5.3 Noise Effects During the Sleep Period

The physiologically acute effects of noise on sleep can be divided into three types: (1) changes in EEG-pattern such as awakenings, transitions towards lighter sleep or EEG changes too short to be classified as sleep-stage changes, (2) body movements, and (3) psychophysiological reactions during sleep, mainly cardiovascular responses.

7.5.3.1 Awakening effects

The methods for detecting awakenings include behavioral awakenings (the participants are requested to press a button whenever they awake, or are asked for awakenings after sleep by questionnaires) and EEG measures of awakening (e.g., Lukas, Dobbs, & Kryter, 1971; Lukas, 1977). Habituation occurs in that during the same night, the awakening tendency decreases with an increasing number of sound exposures per night and across nights, the frequency of awakenings decreases at least during the first eight consecutive nights (Griefahn & Jansen, 1978). A comparison between field studies (noise exposure for several years) and laboratory studies shows that for intense noise peaks from 90 dB, the awakening frequencies are considerably higher in the laboratory but decrease rapidly with the length of exposure (Vallet, Gagneux, & Simonnet, 1980). However, complete habituation is far from being achieved. Another modifying factor is the persons' age, with increased probability of awakening for older persons. Studies suggest that the emergence of the sound pressure from the background rather than the absolute noise level determines the reaction probability (Vallet, Gagneux, & Simonnet, 1980).

For unaccustomed young and middle-aged participants, awakening reactions start occurring from at least 50-55 dB LAmax indoors, probably even at lower levels (12.7 % awakened at 47 dB LAmax of road traffic noise; Thiessen, 1983). At 65 dB LAmax, 10 % of the noise events would produce a wake up, maybe among one third of the exposed persons (30.6 % at 60 dB LAmax; Thiessen, 1983). Sleep stage changes towards lighter sleep can be detected in the laboratory for sound pressure levels exceeding 40 dB LAmax for road, train and aircraft noise (Osada et al., 1968, 1969; Griefahn, 1986). By using questionnaires, Öhrström and Rylander (1990; see also Öhrström & Björkman, 1983) found increased reported awakenings after exposure to intermittent noise at 50 and 60 dBA.

7.5.3.2 Body movements

Body movements have been registered as an objective indication of disturbances of noise during sleep (Muzet et al., 1974). Large body movements have been found to be associated with number of awakenings (Öhrström & Rylander, 1982) or sleep-stage shifts and sleep depth (Dement & Kleitman, 1957). The probability of noise-induced body movements increased with increasing maximum sound pressure level (Öhrström, 1982; Eberhardt, 1987) in the same way as the probability of awakening reactions. However, in contrast to awakenings, there seems to be no habituation to maximum noise level, at least not in 14 nights of exposure (Öhrström, 1989).

No difference has been found in body movements during sleep on exposure to noise levels of 45, 50 or 60 dB LAmax (Öhrström & Rylander, 1990). There was a threefold increase in body movements at all three noise levels at 16 events per night, and a slightly lower increase at 64 events per night as compared to quiet periods of the night. This indicates that a certain habituation to number of noise events takes place in terms of body movements.

7.5.3.3 Psychophysiological reactions

Psychophysiological reactions, such as effects on heart rate, finger pulse and respiration rates have been observed during exposure to noise, while sleeping. These reactions have been shown, both in laboratory and field studies, to be induced by road traffic noise with levels exceeding 40 dB LAmax. Hardly any habituation occurs during and between nights. In contrast to results for EEG responses, children have a higher psychophysiological reactivity than adults. In addition, for these type of reactions, as well as for other arousal effects (Vernet, 1983), the difference between background level and the maximum sound pressure level is of importance rather than the absolute sound pressure level.

Cardiac responses occur at exposure to very low peak noise levels (Jurriens, Griefahn, Kumar, Vallet, & Wilkinson, 1983; Vallet, Gagneux, Clairet, Laurens, & Letisserand, 1983b). Variations in heart rate by 10 beats per min after exposure to road traffic noise at 32 dB LAmax have been shown (Vallet, Pachiaudi, Depitre, Tanguy, & Francois, 1988) but there seemed to be no increase in heart rate at more intense sound pressure levels or at late hours during the night. Although a reduction in sound pressure level does not lead to a reduction in the magnitude of the reaction (Kumar, Tulen, Hofman, van Diest, & Jurriens, 1983), a reduction in the number of noise events reduces the number of reactions (Vallet et al., 1988).

The increase in heart rate after exposure to high-level noise events is generally small and well within the normal variations in heart frequency during the day (Wilkinson, 1984). However, the heart rate response during sleep to a single noise event (i.e., the difference between the maximum and minimum heart rates reached in the acceleratory and the following deceleratory phases) can be 20 to 30 beats, depending on the time of the night and the sleep stage, with no other concomitant sign of an arousal or awakening (Di Nisi, Muzet, Ehrhart, & Libert, 1990). Cardiac changes during sleep are not subjected to habituation. Noise exposure during sleep can increase the release and excretion of adrenaline. This reaction correlates with the change in sleep stage distribution (Maschke, Breinl, Grimm, & Ising, 1993).

7.5.3.4 Changes in sleep stage distribution

The effects of community noise on sleep-stage distribution have mainly been investigated for road traffic noise (Eberhardt, 1987). Fast deep sleep may best be related to the perceived sleep quality. Suzuki, Kawada, Sato, Naganuma, Ogawa, & Aoki (1993) concluded that REM depression is the most sensitive indicator of noise exposure and for enough protection the sound pressure level should be below 45 dB LAmax. Muzet and colleagues (Olivier-Martin Schneider, 1973; Muzet & Olivier-Martin, 1973; Metz & Muzet, 1974), who exposed subjects in the laboratory for jet take-off noises at 77-97 dB LAmax found reduced REM-sleep, with strong rebound effects during the following quiet night. Sound pressure levels of aircraft noise levels exceeding 77-80 dB LAmax may be associated with sleep disturbances observed in newborn babies (Ando & Hattori, 1973).

Several field studies carried out along roads with heavy night traffic indicate that no complete habituation to the normal noisy surroundings had occurred (e.g., Eberhardt, 1987). Jurriens et al. (1983) found no effect on the amount of deep sleep after a reduction of 10 dB in the bedroom. For road traffic noise, Thiessen and Lapointe (1983) found an increase of 2.4 % in deep sleep (compared to a quiet night) at 47 dBA exposure and an increase of 4.8 % in deep sleep at 60 dBA exposure.

7.5.4 After-Effects of Noise Disturbed Sleep

After-effects of noise-disturbed sleep such as perceived sleep quality, fatigue, changes in mood and impairment of performance have been studied both in laboratory and field studies. Long-term effects on psychosocial wellbeing and different medical symptoms in individuals living in heavily noise-exposed areas have been assessed as well.

Results from a joint four-country study show consistent effects on performance after a change in sound pressure level of road traffic noise of about 10 dBA (Jurriens et al., 1983). Perceived sleep quality was used by Lukas (1975, 1977) as a measure of sleep disturbance effects. He combined into a composite sleep quality measure feelings of wellbeing, general sleep quality, and an estimate of how long it took to fall asleep. As compared to behavioral awakening or arousal, he found that this composite sleep quality was better related to different dose measures of aircraft noise than any of the single variables (r = 0.89 as compared to r = 0.50).

Sleep quality after exposure to road traffic noise was also measured by Jurriens et al. (1983) and a 10 dB decrease in the general level of noise was shown to increase sleep quality. Öhrström (1982) found a significant correlation between sleep quality and the maximum sound pressure level of noise from heavy vehicles (60, 70 and 80 dB LAmax), whereas no relationship was obtained for the corresponding LAeq levels.

Decreased mood and increased tiredness have been linked to a decrease in perceived sleep quality (Öhrström, 1982, 1989) which in turn leads to decreased performance. This fact must be looked upon as a health consequence (according to the WHO definition) of night-time noise exposure. Reduced perceived sleep quality has been observed among noise-sensitive persons after exposure to 45 dB LAmax of road traffic noise (Öhrström, Björkman, & Rylander, 1990). This group of moderately or very noise-sensitive persons is estimated to include one third of the general population. Furthermore, performance has been observed to be affected in terms of slower reaction times after exposure to traffic noise at 60 dB LAmax as compared to 50 dB LAmax (Öhrström & Rylander, 1990). Individuals who are more sensitive to noise (as assessed by different questionnaires) report worse sleep quality both in field studies (Öhrström, 1989) and laboratory studies (Öhrström & Rylander, 1982; Öhrström & Björkman, 1988).

Long-term effects of noise must be investigated among individuals who have lived many years in heavily noise exposed areas. Different psychosocial symptoms ("very tired", "anxious/nervous", "a feeling of wanting to be left alone") have been shown to be more frequent in a noisy area (72 dB LAeq) than in a quiet control area (52 dB LAeq). The symptoms could be linked to sleep quality and disturbances of sleep by noise but not to daily activity disturbances. Since tsuch studies have been restricted to a relatively small number of persons (n = 106), further studies are needed to confirm the results.

7.5.5 Influence of Age and Gender

There is some controversy as to the influence of age and gender on noise-disturbed sleep. Some studies have indicated that the sleep of children and young persons is less affected by noise than that of middle-aged or older persons (Dobbs, 1972; von Gierke & C. W. Nixon, 1972). On the other hand, children who are 4-6 years old seem to be particularly disturbed by sudden arousal from sleep stage 4. It has also been reported that babies, who have had gastric difficulties or have suffered brain injury, may be particularly sensitive to noise (Murphy, 1969).

Certain data indicate that women may be more sensitive to noise during sleep than men (Steinicke, 1957; Wilson & Zung, 1966; Lukas, 1972) and that middle-aged women may be particularly sensitive to subsonic jet aircraft flyovers and simulated sonic booms (Lukas & Dobbs, 1972).

7.5.6 Long-Term Effects of Sleep Disturbance by Noise

In spite of several years of exposure complete habituation to noise does not seem to take place. By reducing the noise level indoors, after previous long-term exposure, the quantity of REM-sleep and/or slow-wave sleep has been shown to increase (Vallet, 1979; Vallet et al., 1983a, 1983b; Eberhardt & Akselsson, 1987; Griefahn & Gros, 1986). No habituation has been demonstrated with regard to physiological reactions such as heart rate (Muzet & Ehrhart, 1980) and body movements (Öhrström, 1993b). In addition, perceived sleep quality does not show improvement over time (Öhrström, 1993b).

Sleep or sleep-related conditions are adversely affected by excessive exposure to community noise. Some results even indicate permanent deterioration of the sleep pattern (Vallet, 1979; Vallet et al., 1983a, 1983b; Eberhardt, 1982; Eberhardt & Akselsson, 1987; Griefahn & Gros, 1986; Eberhardt, Stråle, & Berlin, 1987). There is some evidence of long-term effects of noise disturbed sleep on psychosocial health and wellbeing (Öhrström, 1991). Persons exposed to more than 70 dB LAeq, outdoors, report greater difficulties in falling asleep and a more extensive use of sleeping pills and ear plugs as compared to persons living in a more quiet area. Psychosocial wellbeing in terms of depression was reported to be worse among persons living in apartments facing a noisy street. Psychosocial wellbeing was found to be significantly related to sleep quality as well as to annoyance reports to noise.

A cohort study involving 1,006 subjects indicated long-term health effects in the form of noise-induced sleep disturbance (Ising & Rebentisch, 1993b). Data about noise disturbances during the daytime and at night were collected and compared to self-reported diseases. During the day, noise at home had no association with incidence of angina pectoris and hypertension over a period of 11 years. Participants with reported noise-induced sleep disturbances, however, showed a tendency towards increased reported angina pectoris (relative risk: 1.86) and a significant increase in reported hypertension (relative risk: 2.32).

Some experiments have demonstrated that intense noise may improve performance in persons who have been deprived of sleep and are tired, even when they are performing a task that would be highly affected by noise, if sleep had been normal (Corcoran, 1967; Wilkinson, 1963). On the other hand, Le Vere, Bartus and Hart (1972) found decreased performance in a task involving a memory component after nightly exposure to 80 dBA aircraft noise.

Tasks involving monitoring, mental arithmetic, and pattern discrimination were not influenced following nightly exposure to simulated sonic booms (100 N/m^2 at 1-h intervals for 12 nights; Chiles & West, 1972).

On exposure to 80, 85, and 90 dBA tonal pulses with a 22 s interval throughout 24 h for 10 days, Cantrell (1974) found evoked response activity in EEG recordings during sleep but no clearcut effect on various task performance tests. Exposure to a noise of 80 dB LAeq, 15 s, 24 times per night resulted in a significant deterioration in the performance of a choice reaction/memory time test (Le Vere, Morlock, & Hart, 1975).

7.5.7 Effect of Noise Exposure Characteristics on Sleep Disturbances

Special attention should be given to sound peaks in an environment with a low background level, in environments which produce a combination of noise and vibrations, and to low frequency sources because disturbances may occur even though the sound pressure level is below 45 dB LAmax (Vallet, Gagneux, & Simonnet, 1978; Eberhardt, Stråle, & Berlin, 1987). With regard to acute disturbances, it has been shown that intermittent noise of 45 dB LAmax causes a change in sleep intensity. For some test persons, 55 dB LAmax has caused awakenings and "short-lasting reactions" in 50 % of the cases (Eberhardt, Stråle, & Berlin, 1987). A limited field study has even shown awakening at 45 dB LAmax (Öhrström, 1983).

The duration of the noise is also of major importance (Thiessen, 1983). The distribution of sleep stages is affected from 40 dBA (Osada et al., 1968, 1969; Griefahn, 1986; Eberhardt, 1987). Continuous noise affects mainly REM-sleep while intermittent noise can affect sleep stages 3 and 4 as well as REM-sleep (Eberhardt, 1987). The minimum effective level of REM reduction by noise exposure was between 50-60 dB LAeq of continuous pink noise as an average for 4-5 nights. The minimum effective level was estimated to be 45 dBA (Suzuki et al., 1993).

According to the studies conducted so far, equivalent noise energy measurements, such as LAeq, do not correlate with sleep disturbances (Vallet, Gagneux, Clairet, Laurens, & Letisserand, 1983; Vernet, 1983; Öhrström, 1982; Eberhardt & Akselsson, 1987). The reason for this may be found in the noise exposure characteristics which would mean, for example, that it cannot be excluded that highway noise of a large traffic volume may be better estimated in LAeq than intermittent road traffic noise.

The probability of being awakened increases with number of noise stimuli per night. The growth of the dose-response curve, however, becomes gradually smaller and seems to "level off". The frequency of minor reactions (less than a change of one sleep stage) seems to increase linearly with the number of noise events per night (Griefahn & Jansen, 1978). The time interval between two noise events is important for the effect, because the probability of awakening is most pronounced at 40 min intervals between the events (Griefahn, 1977).

A connection has been pointed out between perceived sleep quality and the number of noise events when the sound pressure levels exceed 50 dB LAmax, and the number of noise events is between 40 and 300 (Björkman, Levein, Rylander, Åhrlin, & Öhrström, 1986). At more than 50 noise events per night each of 50 dB LAmax or more, objective sleep disturbances have been observed (Eberhardt, 1982; Eberhardt & Akselsson, 1987). Moreover, objective and perceived sleep quality was reduced when test persons were exposed indoors to maximum sound pressure levels of approximately 45 dB LAmax for more than 40 times per night (Griefahn, 1990). In contrast, in a laboratory study (Öhrström & Rylander, 1990) no subjective effects on sleep were demonstrated at 60 dB LAmax when the number of noise events was below eight. For a good sleep, it is believed that sound pressure levels of approximately 45 dB LAmax should not appear more than 10-15 times per night (Vallet & Vernet, 1991). Noise-abatement measures should aim at reducing the number of intense noise events (Griefahn, 1990).

The period which seems to be the most sensitive, as far as disturbance is concerned, is the first one-third to two-thirds of the night (Eberhardt, 1987). Conversely, Griefahn (1989) demonstrated that cardiac responses during sleep caused by artillery shooting noise were more pronounced in the early morning than during the first hours after sleep onset.

Day noise is suspected to cause general stress reactions which may result in it taking longer to fall asleep at night (Blois, Debilly, & Mouret, 1980). Fruhstorfer, Fruhstorfer, & Grass (1984) showed that the amount of slow-wave sleep was increased during night, which may be interpreted as an increased need for restoration.

Noise-abatement measures will improve the objectively registered sleep quality (Eberhardt, 1982; Eberhardt & Akselsson, 1987; Öhrström, 1983; Wilkinson, 1984; Griefahn & Gros, 1986). With regard to vegetative reactions, no cardiovascular effects have been demonstrated after reduction of noise exposure levels (Kumar et al., 1983).

7.5.8 Variability in Sleep-Disturbance Sensitivity to Noise

Researchers generally assume that there are specific groups who are very sensitive to noise-induced sleep disturbances: for example, persons with a high stress or high anxiety level, tendency to neuroticism, the elderly, and shift workers. However, the literature provides only limited knowledge about individual differences in sleep disturbance tendencies due to noise. Elderly people are awakened far more than the average population by noise during sleep (Eberhardt, 1982) but the impact on the heart rate seems to be more pronounced in children. A slightly higher sensitivity to noise during sleep has been observed for persons with neurotic tendencies (Caille & Bassano, 1977). In laboratory studies “noise-sensitive” persons have reported detoriated perceived sleep quality (Öhrström & Björkman, 1988).

Whether there are differences due to gender is still uncertain.

7.5.9 Relevance of Sound Level Measurements for Sleep

Several laboratory and fields studies indicate that A-weighted equivalent continuous sound pressurelevel is poorly associated with sleep disturbance. Indicators of the intermittent character of the noise have to be taken into account, for example, the number of events exceeding a certain sound pressure level and the difference between maximum and background level (Eberhardt, 1982; Eberhardt & Akselsson, 1987; Öhrström, 1982). A number of different noise exposure indicators have been discussed (Vallet et al., 1983a, 1983b; Griefahn, 1990): L_1 (sound level exceeded during 1 % of the measuring time), LAmax (maximum levels), TNI [Traffic Noise Index: $L_{50} + 4(L_{10} - L_{90})$], and NPL (Noise Pollution Level, accounting for temporal fluctuations). Griefahn (1990) has proposed a method to combine maximum level and number of noise events to determine a critical load for nocturnal noise.

7.5.10 Summary

In order to avoid negative effects on REM-sleep, the equivalent continuous sound pressure level during the sleeping period should not exceed 30-35 dB LAeq for continuous noise indoors. In the case of fluctuating noise, the maximum level is best correlated to sleep disturbances. For isolated exposures as low as 45 dB LAmax, awakenings, changes of sleep depth, etc., have been shown. An increasing number of exposures results in greater risk of adverse effects on sleep.

Special attention should be given to noise sources in an environment with a low background level, to environments where a combination of noise and vibrations are produced and to sources with low frequency components where disturbances may occur even though the sound pressure level is below 45 dB LAmax.

Measures to reduce sleep disturbances during the first part of the night are most effective. As a first attempt efforts should be made to reduce the maximum sound pressure level of noise events and the number of noise events before focusing on reducing the equivalent continuous sound level.

7.6 Psychophysiological Effects

7.6.1 The Stress Response

7.6.1.1 Direct physiological responses

Exposure to noise may evoke several kinds of reflex responses, particularly when the noises are of an unknown or unwanted character. These responses partly reflect primitive defense responses of the body and may also develop after exposure to other stimuli. If the exposure is temporary, the physiological system usually returns to a normal or preexposure state within minutes. Typically no habituation of physiological reactions has been firmly demonstrated, at least not for fluctuating noise (e.g., Vallet et al., 1983a, 1983b).

The reticular and hypothalamic portions of the brain represent the center of the reflex arc, the acoustic pathways represent the afferent branches and the ascending/descending nervous projections represent the efferent branches. Target organs include the visceral organs (heart, blood vessels, intestines, endocrine glands, etc.) which are innervated by the autonomic nervous system and the hypothalamo-diencephalic centers that regulate the alternating rhythms of sleep-arousal, endocrine secretion, and other functions (Bergamini, Bergamasco, Benna, Covacich, & Gilli, 1976).

A sudden change in the acoustic surroundings may activate several physiological systems leading to changes such as increase in heart rate, increase in blood pressure, vascular constrictions, and may even initiate alarm reactions (Andrén, 1982). How big the changes will be depends, for exampel, on individual factors. It is not known whether the direct physiological effects of noise play a role in the pathogenesis of diseases.

7.6.1.2 Indirect noise effects and stress

In real life community noise interferes with a number of activities, for example, recreation, sleep, communication, and concentration. The risk of adverse effects on health must be considered in the light that noise as a stressor may operate through physiological responses modified in complex ways by individual psychological processes.

In field and laboratory experiments, Ising (1983) found no association between human blood pressure responses and noise exposure (traffic noise played back at 60 dB LAmax, 6 h, and intermittent white noise at 100 dB LAmax, 5 min, respectively). It seems that direct effects of short-term exposure to loud levels of noise have little to do with long-term exposures which interferes with daily life activities. Nevertheless, short-term noise-induced disturbances may be associated with the same type of stress reactions which are described as part of the general adaptation syndrome (Selye, 1955, 1956).

Studies suggest that noise-induced stress may increase the excretion of magnesium which may cause a negative magnesium balance especially when the dietary magnesium intake is marginal (Altura, 1979; Ising, 1981; Dyckner & Wester, 1983). Serum magnesium deficiency, in turn, may produce progressive vasoconstriction, vasospasm and ischemia which, given time, may lead to hypertension and coronary heart disease. This theory is supported by the fact that a long-term increase of blood pressure have been demonstrated to be negatively correlated to the concentration of intracellular magnesium (Ising, Havestadt, & Neus, 1985; Ising, Bertschat, Ibe, Stoboy, Goossen, & Hengst, 1986). Emerging data further suggest that low serum magnesium levels may exacerbate the effects on the blood pressure of prolonged noise exposure (Altura, 1993).

There may be a genetic basis for cardiovascular reactions to noise in that persons with normal blood pressure, who belong to families with at least one hypertonic family member, seem to react with more blood pressure elevation in stressful situations than others (von Eiff, Friedrich, Langewitz, Neus, Ruddel, Schirmer, & Schulte, 1981; Theorell, 1990). Physiological reactivity characteristics have not been sufficiently explored to date.

Noise sensitivity has also been put forward as one of the predictors of cardiovascular response to noise. Subjects describing themselves as sensitive to noise have reacted to noise with larger increases in vasoconstriction than their "normal" counterparts (Rövekamp, 1983). Aro (1984) reported that sound pressure level of noise was a significant predictor of blood pressure change only for subgroups of workers. According to Rehm (1983) individual responses to noise may be more highly correlated with symptoms of ill-health than with the noise itself. Furthermore, a person's reports about symptoms of ill-health seem to be related to the quality of sleep. Sensitivity to noise is related to reported sleep problems as well as impaired health (Niveson, 1992).

Controllability over noise as a stressor, necessity and importance of the source of noise and its predictability are currently postulated as factors which may modify the physiological effect of high noise exposures. Uncontrollable stressors are typically appraised as more threatening and are frequently associated with negative effects on health leading to the hypothesis that adverse adrenergic responses occur only after appraisal of noise as a stressor (Kristensen, 1989). Pulles, Biesiot and Stewart (1990) reported differences in subjective health complaints between noise exposed and nonexposed groups to be dependent upon subjects' perceived control over noise, and to be independent of sound pressure level. Atherley, Gibbons and Powell (1970) showed that exposures to noise of large perceived importance (or meaning) are associated with increased complaints, such as tiredness and irritability, galvanic skin responses, and circulating lymphocytes and neutrophils whereas adrenocortical response (urinary 17-ketosteroids) is diminished. Meaningless noise of equivalent intensity (white noise) does not show any of these effects.

7.6.2 Cardiovascular Effects

The overall evidence for the effects of noise on cardiovascular functioning is suggestive of weak to moderate effects of community noise on blood pressure. In addition, there is a potential association between noise-induced hearing loss and cardiovascular disease suggested by Kent, Tolan and von Gierke (1986). The clinical significance of the elevations of blood pressure is not clear. Equivocal conclusions have been drawn from occupational studies of exposure to high levels of continuous noise as well as from research on community noise (Thompson, 1993; Schwarze & Thompson, 1993). Much of this work is methodologically weak in that studies have been based on small, selective samples and have insufficient control for confounders. The cross-sectional nature of most designs does not take into account the temporal relationship between exposure and health outcome. Laboratory studies generally find elevations in blood pressure but are dubious to interpret because of the use of short-term exposures to higher than ambient noise levels.

7.6.2.1 Laboratory studies

Vasoconstriction or vasodilation of blood vessels can be induced by high sound pressure levels of noise during acute exposures. Studies in animals have demonstrated that prolonged exposure to high levels of noise can cause a persistent increase in blood pressure (Rosecrans, Watzman, & Buckley, 1966; E.A. Peterson, Augenstein, Tanis, & Augenstein, 1981).

On exposures of 85-90 dBA levels of work place noise for as long as 9 months, monkeys showed, after the usual short-term startle responses, a trend toward hyporeaction which changed to a pattern of chronic hyperreaction. Compared to control animals under low noise conditions, the noise exposed animals also exhibited orderly changes in the diurnal rhythm of heart rate, blood pressure, and “pauses” in heart rate (E.A. Peterson, Augenstein, Hazelton, Hetrich, Levene, & Tanis, 1984). The fact that these changes persisted for a full month after exposure ceased argues for a chronic effect of noise on blood pressure. It has also been reported that the absence of sound can cause hypertension in rats (Lockett & Marwood, 1973).

As a result of observations made in animal experiments, the relationship between noise exposure and chronic circulatory disease has been investigated in humans. On exposure to 90 dB white noise for 29 min, no effects were observed on cardiac output, cardiac rate, cardiac stroke volume, or pulmonary artery pressure (Etholm & Egenberg, 1964). Klein and Grübl (1969) found an approximately equal distribution of increases and decreases in the pulse rate of the internal carotid artery among persons exposed to 92-96 dB noise for 10 s.

Policemen exposed to traffic noise (60 dB LAeq, several h) showed a slight increase in mean systolic and diastolic blood pressure but some individuals showed a decrease (Ising, 1983). Similarly, among hospital patients experimentally exposed to traffic noise (65 dB LAeq for 12 h) some showed blood pressure decreases and some showed increases in comparison with days of no exposure (Ising, 1983). In regression analysis, poor general condition and pain were associated with decreased blood pressure whereas a hypertensive disposition was associated with increased blood pressure.

Using a binaural technique of noise recording (artificial head), Schwarze, Notbom and Jansen (1993) demonstrated a stronger effect on fingerpulse amplitude (delayed re-regulation) when a multidirectional presentation of industrial noise sources was compared with the conventional unidirectional presentation.

Differences between gender have been demonstrated in an experiment involving exposure to jet aircraft and to railway and pile-driver noise of 70-85 dBA (Osada et al., 1972). Pulse rate fluctuations, vascular constriction, and increase in urinary noradrenaline levels were greater in women than for men. Parrot, Petiot, Lobreau and Smolik (1992) found that gender differences on mean pulse level and heart rate during noise do not persist after rest. From studies by Jansen (1969) and Lehmann and Tamm (1956), it can be concluded that meaningless noise may be associated with peripheral vasoconstriction and reduction of heart stroke value without change of pulse rate and blood pressure. Heart rate response has been suggested to vary as a function of the nature of the noise with the strongest responses being to road traffic noise as compared to pile driver noise, gunfire, and intermittent pink noise of 75 dB LAeq (Parrot et al., 1992).

Sound levels of 62-65 dB LAmax during sleep may lead to increase in heart rate (Vallet et al., 1983b). It has, moreover, been established that a combination of noise and other environmental factors may have a substantially stronger impact on physiological functions than noise alone (Manninen, 1983).

7.6.2.2 Occupational studies

Studies in industrial plants initially focussed attention on the effects of noise on cardiovascular functioning. Several investigations found evidence in human beings of an association between continuous noise exposure and constriction of blood vessels that is primarily manifested in the peripheral regions of the body such as fingers, toes and ear lobes (Lehmann & Tamm 1956). It has been suggested that vasoconstriction, with its concomitant effect on the circulatory system in general, will eventually lead to permanent blood pressure elevations and heart disease (Jansen, 1969; Hattis & Richardson, 1980).

A higher incidence of circulatory problems, peripheral blood flow disturbances, and irregularities of heart rate have been reported among workers exposed to a sound pressure level of noise at 95 dB (Jansen, 1961). Significantly increased blood pressure levels compared with those of control groups have been reported from many studies of individuals chronically exposed to levels of continuous noise exceeding 85 dB in which other risk factors for hypertension are not controlled or only partially controlled. These studies include machineshop operators (Andriukin, 1961), weavers (Parvizpoor, 1976), workers in acetate and polyvinyl chloride industry (Britanov, 1979), shipyard workers (Wu, Ko, & Chang, 1987), textile workers (Zhao, Zhang, Selin, & Spear, 1991), and mechanical and chemical company employees (T. Lang, Fouriaud, & Jacquinet-Salord, 1992). Recent studies of workers exposed to similar noise levels in which major risk factors for hypertension (age, alcohol and tobacco use, body mass index, family history of hypertension) have been taken into account tend to show weak associations between noise exposure and elevated blood pressure, but sample sizes have been small. The duration of exposure has varied from one to 30 years (Aro 1984; Talbott, Helmkamp, Matthews, Kuller, Cottingham, & Redmond,, 1985; van Dijk, Verbeek, & de Fries, 1987; van Dijk, Souman, & de Fries, 1987; Kent, Tolan, & von Gierke, 1986). Zhao et al. (1991) maintain that for individuals susceptible to the effect, the minimum duration of exposure necessary to observe a relationship between noise exposure and blood pressure is about 5 years while T. Lang, Fouriaud and Jacquinet-Salord (1992), and Verbeek, van Dijk and de Fries (1987) suggest that at least 20 years of exposure may be required to produce an effect.

Only one study has demonstrated a dose-response relationship between level of noise and prevalence of hypertension (Zhao et al., 1991). In this study, workshops were selected to cover the range of sound pressure levels from 75 to 104 dB in a textile mill where each of the 1101 female employees had remained in a single workshop with unprotected ears for their entire working life. When the workshop noise measurements were treated as continuous data in a multiple logistic regression, the odds of hypertension increased by 1.2 for each 5 dBA increase in noise, after adjusting for age, working years, salt intake, and family history of hypertension. For methodological information consult, for example, Rothman (1986).

The effects of potential modifiers of noise, namely perceived control of noise, perceived sensitivity, the relationship of the hearer to the noise, and intermittence of noise in noise annoyance, and other stress factors have been suggested from occupational studies such as those by van Dijk, Verbeek and de Fries (1987) and van Dijk, Souman and de Fries (1987).

7.6.2.3 Community studies

Comprehensive community studies of aircraft and traffic noise are scarce but tendencies similar to those found in industrial populations have been observed. Different aircraft noise studies have examined the effects of noise on cardiovascular responses. S. Cohen, Evans, Krantz, and Stokols (1980) compared the blood pressure of children attending schools underneath the flight paths of the Los Angeles International Airport with matched controls in quiet schools. Blood pressure was significantly higher in the children attending the noisy schools. This effect was replicated in a second and a third study (S. Cohen, Evans, Krantz, Stokols, & Kelly, 1981). In the S. Cohen et al. (1981) longitudinal study, analyses proved inconclusive because of subject attrition over the period of one year between the initial measurements and the second measurements. Of particular interest was that attrition from the noisy school sample was not random. Families of children with higher blood pressure were more likely to leave the noise-impacted areas.

Knipschild (1977a, 1977b) and Knipschild and Oudshoorn (1977) examined the effects of aircraft noise on health in the surroundings of the Amsterdam Airport in two studies. In the initial study residents of noise-impacted areas showed higher blood pressure levels and were also more likely to be under medical treatment for cardiovascular disorders, including hypertension. Unfortunately, careful controls for socioeconomic status were not included although the author suggests that the residential areas did not differ drastically in this respect. A dose-response relationship between noise exposure level and blood pressure was suggested. In the second study, the authors analyzed the effects of increased night time flying on medication usage. In the quiet community, purchases of medication remained stable, whereas, in the newly noise impacted community, purchases of medication increased markedly. Based on the studies made around airports, Knipschild (1980) maintained that in environments with heavy noise (67-75 dB LAeq) cardiac diseases, doctors' calls and purchases of medicine are more frequent than in quiet environments (46-55 dB LAeq).

It has been suggested that noise from low flying military aircraft may produce potentially dangerous cardiovascular reactions because, unlike other noise sources, it involves a fast noise level increase at high flight speeds and very high maximum sound pressure levels. Noise exposure in earphones from military high speed, low altitude flight (MLAF; Michalak, Ising, & Rebentisch, 1990) results in significantly higher blood pressure increases with a rapid onset time (30 dB increases within 0.4 s). than to the more gradual onset time (within 4 s). Blood pressure reactivity increased with repetitions of the noise, that is, noise sensitization occurred.

Cross-sectional data on blood pressure were obtained from 430 school children living in a highly exposed MLAF area (minimum flight altitude 75 m, 125 dB LAmax, 65 dB LAeq) and a less exposed neighborhood (minimum flight altitude 150 m, 112 dB LAmax, 59 dB LAeq) (Ising, Rebentisch, Poustka, & Curio, 1990b). The girls' blood pressure, but not the boys', was higher in the highly exposed area but these differences were not verified in a similar field investigation. Also studies of 30-50 years old men exposed to simulated overflight noise (105 dB LAmax) showed acute increases in blood pressure in the immediate post-noise period but no effect on catecholamine secretion (Ising, Rebentisch, Babisch, Curio, Sharp, & Baumgärtner, 1990a). Results of these and other studies of the effects of MLAF-noise are inconclusive for determining extraaural long-term effects in populations (Schmeck & Poustka, 1993; Schulte & Otten, 1993).

Road traffic noise has received attention as a potential stressor on the cardiovascular system with most of the research based on cross-sectional community surveys (Knipschild & Salle, 1979). While a Dutch study (von Eiff & Neus, 1980) did not show a significant association between traffic noise and reported hypertension or ischemic heart disease (IHD), a cross-sectional study in Germany on hypertension did (cf. Neus, Ruddel, & Schulte, 1983). A follow-up of a subgroup of individuals living in a noisy area (63-78 dB LAeq) and a less noisy area ($\leq$ 55 dB LAeq) showed no differences in measured mean blood pressure, but subjects living in the noisy area rated traffic noise as less tolerable than the control group; lower tolerability was related to increased treatment of hypertension (Otten, Schulte, & von Eiff, 1990).

Preliminary results of large prospective investigations in the UK have not given convincing evidence of a dose-response association between sound pressure levels of road traffic noise and nine identified biological risk factors for ischemic heart disease (Babisch, Gallacher, Elwood, & Ising, 1988; Elwood, Ising, & Babisch, 1993; Babisch, Elwood, & Ising, 1993). However, when comparing the lowest noise exposed group (≤ 60 dB LAeq) to the highest exposure group (66-70 dB LAeq), hemostatic and blood lipid factors were slightly shifted, suggesting a slight increase in the expected relative risk for ischemic heart disease (Babisch, 1993). In one community, the associations between traffic noise and blood pressure as well as cholesterol were more pronounced in persons who were also exposed to high levels of work noise as measured by dosimetry (Babisch & Gallacher, 1990). The incidence numbers after 3-5 yrs of follow-up were too small to allow detection of weak associations and adequate adjustment for possible confounding of effect modification. In fact, no evidence of an increased relative risk of ischemic heart disease in men of the highest noise group was found (Babisch, 1993; Babisch, Elwood, & Ising, 1993).

The UK findings are consistent with German and Dutch studies of road traffic and aircraft noise (Babisch, 1993). Hospital- and population-based case-control studies in Berlin (comprising 243 and 4035 men, respectively, aged 35-70 years, predicted levels of road traffic noise ranging from ² 60 to 80 dB LAeq) demonstrated relative risks for the incidence of myocardial infarction of 1.2 and 1.3 among men in the highest noise exposure categories (71-80 dB LAeq). Since even small relative risks (around 1.2) may be relevant for public health because of the relative high number of exposed subjects in the general population (approximately 10%), a pooling of non-significant studies using meta-analytical techniques has been suggested but not conducted yet (Babisch, Elwood, & Ising, 1993).

Although the available data are inconclusive, it appears that traffic noise is, at most, only weakly associated with increased blood pressure or other cardiovascular changes.

7.6.3 Psychoendocrine and Immunological Effects

7.6.3.1 Psychoendocrine Effects

Laboratory studies of both animals and humans have found elevated levels of catecholamines and cortisol on short-term noise exposure (Welch & W elch, 1970; Cavatorta et al., 1987). Catecholamines, principally adren-aline and noradrenaline, are believed to have important cardiovascular effects including elevation of heart rate and blood pressure and, if sustained, damage to arterial linings, cardiac arrhythmias, platelet aggregation, and increased lipid metabolism may occur. Cortisol, which is also an adrenal hormone, has been implicated in suppressed immune system functioning.

Animal studies in mice, rats and guineapigs have revealed a plethora of psychoendocrine effects of exposure to noise at high intensities, for example, depression of corticosterone output (Henkin & Knigge, 1963), increased urinary excretion of adrenaline as an after-response (Ogle & Lockett, 1968), temporary eosinopenia and temporary changes in the adrenal gland (Anthony & Ackermann, 1955), rise in adrenal 11-hydroxy corticosteroid in blood (Horio, Sakamoto, & Matsui, 1972), and increases in plasma corticosterone levels (Rosecrans, Watzman & Buckley, 1966), but also no effects of adrenocortical activity (Anthony, Ackerman & Loyd, 1959).

Human studies of psychoendocrine effects of noise exposure have resulted in increased urinary excretion of adrenaline and noradrenaline after exposure to 90 dB (2,000 Hz) for 30 min (Arguelles, Martinez, Pucciarelli, & Disisto, 1970), changes in the levels of leukocytes, eosinophils, and basophils, as well as in urinary 17-hydroxycorticosteroid after exposure twice a day for 30 min to noise levels of 55, 70, or 85 phon (Tatai et al., 1965, 1967), and increased urinary excretions of 17-hydroxycorticosteroids and noradrenaline after exposure for 2 or 6 hours for several days to noise levels of 40, 50, and 60 dBA (Osada et al., 1973). A cross-sectional study of children around the old airport of Munich (Hygge, Evans, & Bullinger, 1993; Evans, Hygge, & Bullinger, in press) showed increased levels of adrenaline and noradrenaline in children chronically exposed to aircraft noise at the old airport before the close down, compared to a socio-demographically matched control group.

Increased catecholamines during cognitive and mental performance under noise exposure have been noted in human subjects (Franken-haeuser & Lundberg, 1977; Arvidsson & Lindvall, 1978; Lundberg & Frankenhaeuser, 1978). The human work which was also completed in the laboratories suggests that the elevations are a byproduct of human effort to maintain optimum task performance under noise. When effort is reduced and task performance allowed to deteriorate under noise exposure, no significant elevations in catecholamines were noted. In an experimental field study, in which 43 policemen were exposed to 60 dB LAeq of recorded traffic noise, increased urinary noradrenaline excretion was observed (Ising, 1983).

There are insufficient data to justify the conclusion that noise significantly elevates the levels of psychoendocrine activity in human beings. While there are some suggestive laboratory findings, only few studies have been conducted with human subjects in real-life settings.

7.6.3.2 Immunological Effects

The possibility that noise can affect human health by modulating the immune system is based on a body of experiments indicating that noise is a stressor (Schwarze & Jansen, 1990), and studies indicating that stress of various kinds can modulate immune function (Sieber, Rodin, Larson, Ortega and Cummings, 1992). A review by Bly, Goddard and McLean (1993) assesses nine papers published since 1988 to determine if they provide support for the hypothesis that noise can affect health through modulation of the immune system. The results and conclusions from four of the papers were considered to be reliable. However, these results do not provide a consistent basis for a conclusion concerning the potential effect of noise stress on health by modulation of immune function.

The difficulties in assessing the consequences to health from immune system modulation by noise are illustrated by the following examples. Natural killer cell activity is thought to be important in host resistance to some viral challenges and to metastatic spread of tumors. Irwin, Segal, Hauger and T.L. Smith (1989) showed a significant increase in natural killer cell activity in rats, after 10 days of noise exposure but not at 1 or 4 days of exposure. Sieber et al. (1992) found small reductions in natural killer cell activity after acute exposure of healthy male human volunteers to uncontrollable noise, but not to controllable noise. Folch, Ojeda and Esquivel (1991) found that thymulin, a hormone affecting thymus function, showed a reversible increase in concentration in the blood of mice after noise stress. Kugler, Kalveram and Lange (1990) showed a statistically significant reduction by about 25% in two lymphocyte subject populations after acute, but not chronic, stress.

Taken as a whole, no consistent conclusions can be drawn since two studies on animals show immune system stimulation, one on humans shows suppression, and one on animals shows suppression for acute exposure but no effect for chronic exposure.

7.6.4 Startle Reflex and Orienting Response

Certain noises, especially those of an impulsive nature, may cause a startle reflex, even at low levels. The startle (Molinie, 1916) occurs primarily in order to prepare for action appropriate to a possible dangerous situation signaled by the sound. It consists of contraction of the flexor muscles of the limbs and the spine and a contraction of the orbital muscles that can be recorded as an eye blink. It may be followed by an orienting reflex that causes the head and eyes to turn towards the source of a sudden sound in order to identify its origin (Thackray, 1972). The startle reflex can sometimes be followed by a fright reaction, in which case the effects on the circulatory system become more pronounced. Skin conductance is also influenced due to alterations in perspiration (Klosterkötter, 1974; Niveson, 1992).

The presence of the startle and orienting reflexes is detected, i.a., by noting behavioral reactions or by the electrophysiological study of muscle tension and activity (Galambos, Rosenberg, & Glorig, 1953; R.C. Davis, Buchwald, & Frankmann, 1955). Although low level sound stimulation may be sufficient in abruptness and information to induce a startle reflex, the fact that a person has experienced some degree of startle, may often only be recorded electrically. For meaningless noise of various types, it has been observed that orienting reflexes are elicited at the very beginning of a series of stimuli; but that habituation occurs and possibly also a masking effect of background noise. At more intense levels, habituation is less marked.

Startle reactions occur in connection with sonic booms and increases with the intensity of the boom (outdoors 60-640 Pa, indoors 20-130 Pa; Rylander, Sörensen, Andrae, Chatelier, Espmark, T. Larsson, & Thackray, 1974). The possible long-term effects on human subjects of sustained repetition of acute startle reactions are not known.

7.6.5 Effects on the Sense of Balance

A high level of noise may influence balance equilibrium because of the stimulation of the vestibular sense organ. However, available data concerning this subject are both inconclusive and inadequate. Complaints of nystagmus (rapid involuntary side-to-side eye movements), vertigo (dizziness), and balance problems have been reported after noise exposure in the laboratory, as well as in field situations. The levels needed to cause such effects in personnel working on jet engines were quite high, typically, 130 dB or more (Dickson & Chadwick, 1955). Less intense sound pressure levels ranging from 95 to 120 dB also disturb the sense of balance, if there is unequal stimulation of the two ears (C.W. Nixon, C.S. Harris & von Gierke, 1966; C.S. Harris, 1974).

7.6.6 Bodily Fatigue

Noise-induced strain on the body may cause fatigue, either directly or indirectly through interference with sleep. A variety of environmental agents as well as conditions within the individual may cause symptoms of fatigue.

Symptoms of extreme fatigue have been reported by subjects exposed to intense levels of infrasound (Mohr, Cole, Guild, & von Gierke, 1965). On the other hand, no simple relationship was found between noise levels and feelings of fatigue among workers from workshops with five different levels of sound intensity ranging from 50 to 125 dB (Matsui & Sakamoto, 1971). The precise role of noise as a causal or contributive factor in bodily fatigue has not yet been established.

7.6.7 Effects on Physical Health

Exposure to noise may result in a variety of biological responses. Most of the information has been derived from short-term studies on animals and human subjects, but it has been postulated that, if provoked continuously, such responses would ultimately lead to the development of clinically recognizable physical or mental disease in human beings. Numerous clinical symptoms and signs have been attributed to noise exposure including nausea, headache, irritability, instability, argumentativeness, reduction in sexual drive, anxiety, nervousness, insomnia, abnormal somnolence, and loss of appetite (Jirkova & Kromarova, 1965).

From a theoretical point of view, an assessment of the causal relationship between noise exposure and nonspecific health effects presents difficulties. Increases in blood pressure level, heart disease, gastric ulcers, and other stress-related syndromes have a multifactorial origin. It is difficult to exercise sufficient control over all relevant risk factors in epidemiological studies, particularly as several of the risk factors such as social class, personal habits, and personality characteristics are difficult to define.

Both occupational studies and aircraft noise studies have found associations between noise and gastrointestinal symptoms, self-reports of general physical health status, and visits to the physician for physical symptoms. Some studies fail to replicate these effects. However, some studies have also found links between aircraft noise and neonatal health (S. Cohen & N. Weinstein, 1982; S. Cohen, Evans, Stokols, & Krantz, 1986).

In a study on workers exposed to intense noise (Jansen, 1962), there was evidence of a higher prevalence of circulatory problems and a higher incidence of fatigue and irritability in the exposed group than in the controls. A. Cohen (1976) studied the medical records of 500 workers working in noisy areas (95 dB LAeq or more) and those of a group matched for age and length of plant experience, working in quieter areas (80 dB LAeq or less). The noise-exposed workers tended to have more symptomatic complaints and more diagnosed medical problems. It is difficult, however, to relate these findings to noise only, since noisy work places are, presumably, also work places with other health hazards. Benkö (1959, 1962) examined workers exposed to sound pressure levels of 110-124 dB and found a persistent narrowing of the visual field as well as a decrease in color-perception. The second finding could not be verified in studies reported by Kitte and Dieroff (1971).

Methods of studying industrial populations have shortcomings that make it difficult to draw conclusions concerning other populations. The group is always selected, that is, those not able to tolerate the exposure and those developing medical symptoms may have left. The group usually consists of males in good physical condition and older age groups are underrepresented.

In a study on aircraft noise around a German airport, no signs of disease were found in a thoroughly examined sample of the population exposed to 82-100 dBA aircraft noise (Deutsche Forschungsgemeinschaft, 1974). Tarnopolsky, Hand, Barker, and Jenkins (1980), studying the effect of aircraft noise, found that many acute symptoms showed an increase with noise, but chronic symptoms were more common in low noise conditions. Monotonic dose-response relationships were not clearly visible.

The potential noise-induced effects on physical health are not well established with respect to community exposures. The available data do not permit one to draw definite conclusions.

7.6.8 Summary

Studies have shown that noise affects both mental and physical wellbeing. It has been postulated that noise acts as a general stressor and as such may activate several physiological systems leading to changes such as increases in blood pressure and heart rate and vasoconstriction. The magnitude and duration of these effects are determined in part by individual susceptibility, lifestyle behaviors and environmental conditions. However, laboratory and clinical data are insufficient to conclude that noise significantly elevates the levels of psychoendocrine activity in humans.

By far the greatest number of occupational and community studies have focused on the possibility that noise may be a risk factor for cardiovascular disease. Many studies in occupational settings have indicated that workers exposed to high levels of industrial noise for durations of 5 to 30 years have significantly increased blood pressure compared to workers in control areas. Similarly, there has been a tendency for blood pressure to be higher among persons living in proximity to airports and on streets with higher levels of traffic noise than among control subjects. Recent investigations in which major risk factors for hypertension have been taken into account tend to show much weaker associations.

Cross-sectionally designed studies, which cannot provide information on the temporal relationship between noise exposure and onset of disease, and, thus, not on causality, continue to dominate the literature. Preliminary results from prospective studies (Elwood, Ising, & Babisch, 1993; Babisch, 1993; Babisch, Elwood, & Ising, 1993) give no convincing evidence of an association between long-term exposure to traffic noise and blood pressure or other known risk factors for heart disease. Although very large, the sample size is still too small to be able to detect true weak associations and to take into account the many confounding variables and factors believed to modify the noise-to-disease relationship. Potential modifiers of noise effects which often are not considered include perceived control of noise, noise sensitivity, noise annoyance and total noise load. Further prospective studies are needed to determine the relationship between noise exposure and cardiovascular health and to identify the groups at risk, if any, to these effects.

Generally, it can be said that it is easier to become habituated to noise which manifest itself as continuous noise. The possibility of becoming habituated and the cost to be paid for this depend on the individual. Everyone, even those who have become habituated to noise, will experience that activation after a habituation period (dishabituation) will result in a load (cost). In order to achieve habituation in the waking state for an intermittent noise source, a frequency of at least 10-15 events per hour is required. Noise-abatement measures should concentrate first and foremost on the noise peaks of an otherwise continuous noise.

Risk groups (sensitive individuals) do not consist of just the group with impaired hearing (10 % of the population) but in reality of a much larger group. The noise load for these persons may be assumed to be more serious than shown by the traditional input-response relationships.

7.7 Mental Health Effects

Exposure to high levels of occupational noise has been associated with development of neurosis and irritability and also environmental noise with mental health (Evans, 1982; S. Cohen et al., 1986). Herridge and Chir (1972) have suggested that noise is not a direct cause of mental illness but that it might accelerate and intensify the development of a latent neurosis.

Studies of the records of some 124,000 persons living in a noisy area around London Heathrow Airport and in a quieter area nearby revealed a higher rate of admittance to mental hospitals in the noisy area (Abey-Wickrama, A' Brook, Gattoni, & Herridge, 1969). However, the design of the epidemiological study was questioned by other workers (Chowns, 1970) and the finding could not be verified in a later investigation (Gattoni & Tarnopolsky, 1973). The relationship between noise exposure, the presence of mental disorders, and annoyance was studied in a field investigation on 200 persons, half of whom lived near London Heathrow Airport. No association was found between noise exposure and mental morbidity, but symptoms of mental disorders were more common among those who reported that they were very annoyed by the noise (Tarnopolsky, Barker, Wiggins, & McLean, 1978).

The relationships among noise annoyance, noise sensitivity and mental morbidity have been found to be complex and not yet well differentiated (Tarnopolsky et al., 1980a; Stansfeld, C.R. Clark, Jenkins, & Tarnopolsky, 1985; Stansfeld, 1988, 1992). Noise sensitivity was shown to be a relatively stable trait and was demonstrated to be a powerful predictor of noise annoyance. It was found to be associated with current psychiatric problems only. Evidence from these studies further suggest that noise sensitivity may be a self-perceived indicator of vulnerability to stressors in general and may also be indirectly measuring a subclinical level of psychological morbidity.

The consumption of tranquilizers and sleeping pills has been proposed as an indication of latent disease or mental disturbance in noise-exposed communities. Grandjean (1974a, 1974b) reported an increase in the consumption of such drugs among persons exposed to aircraft noise. Findings to the contrary were reported from a study of persons living in the neighborhood of Munich Airport (Deutsche Forschungsgemein-schaft, 1974). A possible explanation for the discrepancy between the two studies is the manner in which the questions concerning drug consumption were posed and related to aircraft noise exposure.

7.7.1 Definition of Mental Health Concepts

A classification of criteria for mental health has been made by Kasel and Rosenfield (1980) into: (a) indices based on treatment data, (b) psychiatric signs and symptoms, (c) indicators of mood, wellbeing, satisfaction, etc., (d) indices of functional effectiveness and role performance, and (e) indices derived from notions of positive mental health, for example, adequacy of coping. Freeman (1984) defines mental health in common sense and pragmatic terms as the absence of identifiable psychiatric disorder according to current norms.

Mental health in noise research covers a variety of symptoms, ranging from anxiety, emotional stress, nervous complaints, nausea, headaches, instability, argumentativeness, sexual impotency, changes in general mood and anxiety, and social conflicts, to more general psychiatric categories like neurosis, psychosis and hysteria. McLean and Tarnopolsky (1977) in a review of literature on noise and mental illness, quote terms like “a minor affective illness characterized by anxiety”, “symptoms compatible with minor affective illness”, “mental health status factor”, “tiredness and irritability”.

7.7.2 Mental Disorders, Symptoms, and Indicators

A high proportion of psychological and psychosomatic complaints was found in a highly exposed aircraft-noise area (Knipschild, 1976). Studies, reviewed by McLean and Tarnopolsky (1977) show correlations with indicators of mental health. On the other hand, Gattoni and Tarnopolsky (1973) could not find significant relationships when controlling for demographic factors, and Grandjean (1974a, 1974b) found no correlation between symptoms and exposure. Preliminary results from a prospective traffic noise study in the UK showed a strong association between noise sensitivity and psychiatric symptoms, but no association between noise level at baseline and later development of psychiatric disorder (Stansfeld, Gallacher, Babisch, & Elwood, 1993).

In a review of evidence relating noise to mental illness, McLean and Tarnopolsky (1977) concluded that evidence is scanty and much of it based only on clinical impression. Several studies relating community noise to mental health may have confounded noise exposure and demographic variables; in some studies questions were worded so that respondents could attribute their annoyance to aircraft noise (S. Cohen & N. Weinstein, 1982; S. Cohen et al., 1986). In an examination of data and review of past work, Stansfeld (1992) concurs and argues that while noise exposure may lead to minor emotional symptoms, the evidence of elevated levels of aircraft noise leading to psychiatric hospital admissions and psychiatric disorder in the community is contradictory. The methodological problems include: the retrospective character of most studies, small differences, selection of only the severest cases of mental distress, socially accepted deviations of normality, self-selection to mental hospitals or general practitioners, and the nature of mental health effects (causing distress or merely aggravating it).

Tarnopolsky et al. (1978) report a marked association between annoyance by aircraft noise and psychiatric symptoms. However, the screening instrument used for psychiatric disorders (Goldberg, 1972) and the study approach reflect presuppositions on the validity of the concepts used. Tarnopolsky et al. (1978) distinguish between symptoms produced by noise annoyance and symptoms due to neurotic illness and conclude that sensitivity to noise is a predisposing factor for psychiatric morbidity. This is confirmed by the one prospective study of noise sensitivity and psychiatric disorder (Stansfeld et al., 1993). Noise sensitivity may be an indicator of subclinical psychological morbidity. The effect of noise sensitivity on psychiatric disorder was virtually eliminated when a measure of trait anxiety was included in the analysis.

Other indicators for mental health problems are the use of medical drugs (e.g., Watkins, Tarnopolsky, & Jenkins, 1981) and admission to mental hospitals (Abey-Wickrama et al., 1969; Herridge & Chir, 1972; Gattoni & Tarnopolsky, 1973; McLean & Tarnopolsky, 1977; Meecham & Smith, 1977; Åhrlin & Öhrström, 1978; Tarnopolsky et al., 1978; Tarnopolsky et al., 1980; Jenkins, Tarnopolsky, & Hand, 1981; Watkins, Tarnopolsky, & Jenkins, 1981). A variety of psychiatric variables is used. They vary according to specificity and generality, place of contact with medical agencies, and use of psychotropic medicine. Reliability and validity studies are almost absent and definitions are poor. Seemingly no clear conceptual distinction has been made between mental health and other health effects.

If noise causes annoyance and frustration, it seems plausible that prolonged exposure could cause or aggravate mental illness (S. Cohen & N. Weinstein, 1982; S. Cohen et al., 1986; Evans & S. Cohen, 1987). People with low social support might be more likely to be hospitalized for noise-related mental problems. Some studies have demonstrated an association between mental hospital admissions and level of aircraft noise (Abey-Wickrama et al., 1969; Herridge & Chir, 1972) and living in noisy areas (Meecham & Smith, 1977). On the other hand, Tarnopolsky et al. (1980) could not find consistent relationships between noise exposure and admission to mental hospitals. Kryter (1990) re-analyzed data of Jenkins, Tarnopolsky, & Hand (1981), adjusting for unemployment and the percentage of people in rental accommodation. The result was a significant positive correlation between aircraft noise exposure and admission rate at two of the three psychiatric hospitals examined.

Watkins, Tarnopolsky and Jenkins (1981) found increased use of psychotropic drugs by people who report that they are highly annoyed by noise. Importantly, this association occurred without a relationship between medication use and noise exposure. Less catastrophic indexes ought to be examined (S. Cohen et al., 1986), including standard psychological symptom profiles (e.g., anxiety, depression).

Despite its weaknesses, the evidence points to possible negative effects of community noise on mental health, manifested in the presence of psychiatric symptoms and mental hospital admission rates. However, firm conclusions are not warranted at this time. There are several reasons for caution (B. Berglund, Lindvall, & Nordin, 1990):

(1) There is no conceptual clarity on psychiatric classifications. This reflects the general lack of conceptual clarity in the field of psychiatry and clinical psychology.

(2) The conceptual and methodological status of “sensitivity to noise” is not satisfactory (Job, 1993). Stansfeld (1992) has recently reported evidence of a possible direct relationship between sensitivity and mental health regardless of noise (see also Stansfeld et al., 1985).

(3) Confounding factors such as socioeconomic status are not always kept constant in the studies reviewed.

(4) Studies are often correlational and do not permit decisive causal inferences.

(5) Theoretical models are absent. The current theoretical notions are mostly restricted to ad hoc and a priori explanations.

(6) The relationship between mental health, general health, and stress is explicated. Noise sensitivity is put forward as an explanatory construct with regard to mental health. But this concept of “sensitivity to noise” as measured introduces a serious problem of validity. The scales and the definitions of sensitivity to noise raise the following interrelated problems with regard to:

(a) Circulatory definitions; there is no independent definition of noise sensitivity with respect to annoyance and other effects of noise (e.g., task interference).

(b) Reliability; often one question is asked to estimate sensitivity to noise.

(c) The self-report character of the scales and the absence of other methods of measurement cause significant problems.

7.7.3 Summary

Exposure to high levels of occupational noise has been associated with development of neurosis and irritability and exposure to high levels of environmental noise with mental health. Noise is not believed to be a direct cause of mental illness but might accelerate and intensify the development of latent mental disorders. The relationships among noise annoyance, noise sensitivity and mental morbidity is complex and not yet well differentiated

The consumption of tranquilizers and sleeping pills has been proposed as an indication of latent disease or mental disturbance in noise-exposed communities. The evidence relating noise to mental illness is scanty and much of it is based only on clinical impression. Several studies relating community noise to mental health may have confounded noise exposure and demographic variables.

Despite its weaknesses, the evidence points to possible negative effects of community noise on mental health, manifested in the presence of medical drug use, psychiatric symptoms and mental hospital admission rates. Any firm conclusions are not warranted at this time.

7.8 Performance Effects

7.8.1 Task Performance and Productivity

Noise can interfere with complex task performance. Tasks that demand continuous and sustained attention to detail, require attention to multiple cues, and require large working memory capacity are all susceptible to adverse effects of noise. Evidence for disruptive effects of noise on industrial productivity is unclear and largely dependent upon poorly designed studies.

Noise causes brief periods of inefficiency when sustained visual attention is required. Under these conditions overall levels of performance may not suffer but momentary lapses are common. These errors appear to be related to a shift in response criteria rather than signal detectability per se with faster responses and higher frequency of false alarms (person responds to signal when it is not present) (Broadbent, 1981; S. Cohen et al., 1986). Tasks which require continuous and careful monitoring of signals or cues (e.g., warning systems) may be negatively affected. On the other hand, since noise increases alertness (arousal), monotonous and boring tasks may be performed better under noise conditions because the organism remains closer to an optimal level of overall arousal.

Noise has a persistent and well documented effect on tasks that require attention to multiple cues, for example, when monitoring two different signals (dual tasks) (S. Cohen et al., 1986; Smith, 1989). Specifically, errors occur in the task(s) of secondary importance as defined either by instructions or payoff matrices (Hockey, 1979). Cues that are secondary in importance are missed and/or responded to more slowly under noisy conditions. The effect is not due to a narrowing of attention as originally thought.

Two types of memory deficits have been uncovered under noise exposure: incidental memory and memory for materials that the observer was not explicitly instructed to focus on during the learning phase (S. Cohen et al., 1986; Hockey, 1979; D.M. Jones, 1984). For example, when presented semantic information under noise, recall of the contents was unaffected by noise but subjects were significantly less able to recall in which corner of the slide the word had been located (Hockey, 1979). There is also some evidence that the lack of helping behavior noted under noise exposure may be related to inattention to incidental cues (S. Cohen & Lezak, 1977).

Subjects appear to process information faster in working memory during noisy performance conditions but at a cost of available memory capacity. For example, in a running memory task in which subjects are required to recall in sequence letters that they have just heard, subjects recall recent items better under noisy conditions but make more errors farther back into the list (Hockey, 1979).

Noise exposure consistently produces negative performance aftereffects. Deficits on tasks immediately following noise exposure have been found in proofreading and in persistence on challenging puzzles (S. Cohen, 1980). The uncontrollability of noise rather than the intensity of the noise appears to be the most critical variable (S. Cohen et al., 1986).

There are few studies that unequivocally show a relation between sound pressure levels of noise and productivity. Most of the studies are poorly designed and many studies find few if any negative effects. On the other hand, productivity has been shown to increase in noisy industrial settings when ear protection devices are worn (Broadbent, 1971; A. Cohen, 1974; Smith, 1989).

In the complexity of interrelated factors intervening in the effects of noise on humans during work, attention has been paid to self-reported noise sensitivity. Subjects highly sensitive to noise performed significantly poorer in deep mental processing (i.a. difficult mental arithmetic) as compared to subjects less sensitive to noise (Arvidsson & Lindvall, 1978; Belojevic, Öhrström, & Rylander, 1992) .

7.8.2 Noise as Distracting Stimulus

Noise can act as a distracting stimulus, depending on the meaningfulness of the stimulus and the psychophysiological state of the individual. According to a widely accepted theory in psychology, the human sensory system receives more information than can be analyzed by the higher centers. In order to screen out useless information, such as noise, the concept of a “mental filter” has been developed (Broadbent, 1972). This “mental filter”, however, has the following limitations:

(a) it tends to reject or ignore unchanging signals over a period of time, even though they may be important, as in vigilance tasks;

(b) an individual’s state of arousal, stress, or fatigue may hinder the mental filter’s ability to discriminate; and

(c) it can be overridden by irrelevant stimuli that demand attention because of novelty, intensity, unpredictability, or learned importance.

A novel event, such as the start of an unfamiliar noise, will cause distraction and interfere with many kinds of task. This will be equally true, however, of the sudden stopping of a familiar noise; and, in each case, the effect will disappear once the novelty has worn off. These reaction patterns are well established experimentally (Kryter, 1970, 1994; Glass & Singer, 1972).

Hebb (1955) suggested that changes in stimulation not only initiate appropriate cortical responses but also activate or arouse areas of the cerebral cortex other than those involved in the response. This wide arousal activity originates in the reticular formation, a portion of the central nervous system, and affects the person's psychological state as well as physiological systems.

Too low a level of arousal can mean poor performance. On the other hand, too high a level may cause inefficiency through over-reaction to distraction, leading to incorrect responses. Thus, exposure to loud noise might increase or decrease task performance depending on the previous state of arousal.

7.8.3 Cognition and Reading

Although there is no conclusive proof that noise causes deficits in reading acquisition, there is an abundance of cross-sectional studies and two longitudinal studies showing negative associations between chronic exposure to high noise sources (principally aircraft or road traffic noise) and deficits in reading acquisition among children (S. Cohen et al., 1986; Evans, 1990; Hygge, Evans, & Bullinger, 1993; Evans, Bullinger, Hygge, Gutman, & Aziz, 1994; Hygge, Bullinger, & Evans, 1994; Evans, Hygge, & Bullinger, in press). One of these cross-sectional studies also revealed a relatively consistent dose-response relationship between noise exposure to aircraft noise and the degree of delay in reading acquisition (K.B. Green, Pasternack, & Shore, 1982). The effects appear to be stronger for children in the later elementary grades which may be simply a function of longer exposure duration. There is also some evidence that children exposed both at school and at home to loud ambient noise sources are more likely to suffer reading deficits in comparison to those only exposed at school. Children with preexisting speech or language difficulties may be the most vulnerable to these harmful effects. Furthermore, a negative relation is suggested between noise levels in the home and cognitive development among infants and preschool children (Evans, 1990; Wachs & Gruen, 1982).

A combined cross-sectional and longitudinal study has been conducted on children around the old and new airports of Munich, before and after the switch of location. The findings showed impaired reading and word-list performance, and long-term recall of a text in children chronically exposed to aircraft noise at the old airport before the close down, compared to a socio-demographically matched control group. However, after the close down of the old airport, the difference on those measures were no longer significant. At the new airport, there were no corresponding impairments in cognitive functions on the same measures from before to after the opening of the new airport (Hygge, Evans, & Bullinger, 1993; Evans et al., 1994; Hygge, Bullinger, & Evans, 1994; Evans, Hygge, & Bullinger, in press). Results from class-room experiments with children show that aircraft noise exposure is associated with more impairment of long-term text-recall (one week) than road traffic noise when presented at the same level of 55 dB LAeq (Hygge, 1993b, 1994). Exposure at 66 dB LAeq, was associated with a significant impairment of long-term recall on exposures from aircraft and road traffic noise, as well, but not on exposures to railway traffic noise and verbal noise (foreign languages).

One possible explanation for the relations between chronic noise exposure and reading deficits is that children chronically exposed to noise may suffer from deficits in auditory discrimination (S. Cohen, Glass, & Singer, 1973). Children exposed to noise where they lived had deficits in auditory discrimination and reading when tested under quiet conditions. The deficits in auditory discrimination largely explained the association between ambient residential noise levels and reading deficits.

7.8.4 Tasks Involving Motor Activities

It appears that steady noise has little, if any, effect upon many tasks, once it has become familiar. Such tasks include tracking or controlling tasks where sound levels are fairly continuous and where average, rather than instantaneous, levels of performance are important (Broadbent, 1957; Kryter, 1970, 1994). Many mechanical or repetitive tasks found in factory work would fall into this category. Generally it can be concluded that noise is likely to reduce the accuracy rather than the total quantity of work (Broadbent, 1971). However, it appears that moderate levels of noise increase arousal during monotonous tasks. McGrath (1963) found that various auditory stimuli at 72 dB improved visual vigilance performance.

7.8.5 Summary

The effects of noise on human performance are very complex. Acute noise exposure appears to disrupt tasks that demand attention to multiple cues, tasks in which high levels of working memory capacity are required, and tasks where continuous and detailed attention to frequent signals is required. There are well documented aftereffects, particularly of uncontrollable noise, on human performance that demands sustained effort. Chronic noise exposure impacts reading acquisition in children. This may be related to deficits in auditory discrimination associated with chronic noise exposure in the home or at school. No current theory can adequately predict under what conditions noise will disrupt cognitive performance.

7.9 Effects on Residential Behavior and Annoyance

Sound environments produce a number of social and behavioral effects on residential behavior and annoyance (for reviews see J.D. Miller, 1978; D.M. Jones, 1984; D.M. Jones & Chapman, 1984; Lara Saenz & Stephens, 1986; Guski, 1987), including:

(a) Overt everyday behavior patterns (e.g., opening windows, using balconies, TV and radio use, writing petitions, complaining to authorities).

(b) Human performance on specific test tasks (school achievement, vigilance, choice-reaction time, short-term memory, air traffic control, etc.).

(c) Social behavior (aggression, unfriendliness, engagement and participation, etc.).

(d) Social indicators (residential mobility, hospital admissions, drug consumption, accident rates, etc.).

(e) Changes in mood (less happy, more depressed mood, etc.).

The effects of community noise on social and behavioral variables are often complex, subtle and indirect. Many of the effects must be assumed to be the result of interactions with a number of nonauditory variables.

7.9.1 Definition and Measurement of Community Annoyance

Community reaction to noise may involve considerably more than just annoyance. People may feel a variety of negative emotions when exposed to community noise, and may report anger, disappointment, dissatisfaction, withdrawal, helplessness, depression, anxiety, distraction, agitation or exhaustion (Job, 1993). Although annoyance may arbitrarily be defined as a “feeling of displeasure associated with any agent or condition known or believed by an individual or a group to be adversely affecting them” (Lindvall & Radford, 1973), more recent data indicate that the term annoyance does not cover all the negative reactions (Job, 1993). However, studies which have considered more than annoyance as a measure of subjective reaction have produced broadly similar results to those studies examining annoyance only (e.g., Bullen & Hede, 1986; Job & Hede, 1989; Bullen, Hede, & Job, 1991; Job, Bullen, & Burgess, 1991).

In urban societies, annoyance from noise exposure may be present in a majority of the inhabitants. In terms of the numbers affected, annoyance is probably much more widespread than other overt effects caused by a noise environment.

A broad range of psychophysical effects has been considered in laboratory and field studies of community noise. The subjective experience with noise can be conceptualized along a number of different dimensions which vary in the extent to which they emphasize the emotional as opposed to cognitive aspects of human reactions: loudness, noisiness, and annoyance. Virtually all of the work in field surveys has examined annoyance. Over 300 field surveys have been conducted of reactions to noise in residential communities (Fields, 1991, 1993b). The relationship between annoyance and sound pressure level has been examined in most of the surveys. The exact form of the relationship varies considerably from study to study, depending on the subject of the survey question, the degree of annoyance measured, and various measured and unmeasured characteristics of the population. The most widely used dose-response relationship relates a relatively high degree of annoyance to sound level (Schultz, 1978; Fidell, Barber, & Schultz, 1991). For this, as for any other community noise reaction relationship, there is a steady increase in annoyance with sound pressure level. Thus, there are no strong discontinuities at moderate or high sound pressure levels which could serve as a basis for setting limits to noise exposure. At very low sound pressure levels there is such a considerable agreement among residents that variability is only a small problem. At moderate and intense sound pressure levels, however, there is enormous variability in individuals' and to a lesser extent, communities' responses to noise (Fields, 1983, 1993b). The causes of the variations are only partially understood (Job, 1988a).

Annoyance is affected by both the highest level of noise generated by the source and by the number of such noise events which occur. Methods for combining these effects has been extensively studied. The social surveys have not been able to exactly specify the relationship or to refute totally any competing theories.

The process of human response to community noise begins with perception of the noise stimulus. The outcome of the perceptual process will create the basis for a possible feeling of annoyance. This feeling may be modified by many psychosocial variables, such as living conditions, attitudes towards the noise source, previous noise exposures, socioeconomic variables, etc. Whether or not a feeling of annoyance is ever given behavioral expression depends also on a number of intervening variables. When studying annoyance, both the perceived noise and the perceived quietness should be considered (Guski, 1983).

So far, noise abatement is exercised by reducing the sound pressure level of a community noise. It is based on major relationships found between external noise and its adverse effects on the human population. For the adverse effect to be coupled to the noise and not to another environmental agent, a person has to be able to hear it. Langdon (1987) concludes that although, in some socio-physical surveys noise exposure can account for over 85 % of the variance in expressed annoyance of a community, the prediction of individual responses remains poor. In a review of the literature, Job (1988a) concludes that only a small percentage (typically less than 20%) of the variation in individual reaction is accounted for by noise exposure. Variables, such as attitude to the noise source and sensitivity to noise, account for more variation in reaction than does noise exposure. These results seem to imply that the perception of the noise contributes little to noise annoyance, unless individual differences in perception are large in field settings. However, from a practical point of view, today physical sound measures like Leq and Lmax may be the only basis for predicting annoyance to control community noise and to protect people from unacceptable high annoyance level. Indeed, studies show that Leq sometimes is a useful measure for estimating annoyance (Vos & Geurtsen, 1987; Buchta, 1993).

As a consequence of the low amount of explained variance, the physical noise characteristics seem to be of less importance to reported annoyance than psychological or social factors of more complex nature. It is obvious that there are large gaps in the current knowledge, and yet there is no theory on how different factors contribute to the adverse effects of noise. Most knowledge on sound perception emanates from laboratory experiments with tones or white noise. The psychophysics of complex sounds has been concerned mainly with speech or music and, only recently, have researchers taken an advanced interest in real community noises. For example, the loudness of aircraft noises has been found to be a power function of its sound pressure level. The exponent is somewhat lower for community noises (0.48, relative to LAmax) than for tones (0.60) (B. Berglund, U. Berglund, & Lindvall, 1975a). B. Berglund, U. Berglund and Lindvall (1976) also showed that, at low sound pressure levels (below 50 dB LAmax), community noises like those from pile driver, jack hammer, and typewriter, are relatively more annoying than aircraft noise. This fact may be related to the strongly time-limited character of the former noises. For more intense sound pressure levels, the reverse relationship holds. This means that for medium and high sound pressure levels, the annoyance of repetitive community noises becomes mainly loudness-based (B. Berglund, U. Berglund, & Lindvall, 1987).

7.9.2 Effects on Social Behavior

Noise may reduce helpfulness and potentiate aggressiveness. There is some evidence that noise gives rise to extreme judgments of others (Siegel & Steele, 1980). Willingness to help has been suspected to be less during exposure as well as during a time period after exposure (Korte, Ympa, & Toppen, 1975; Korte & Grant, 1980; Mathews & Canon, 1975; Page, 1977). Noise is not sufficient to produce aggression, but in combination with provocation or preexisting anger/hostility, it potentiates aggression (Konecni, 1975; Chapman & D.M. Jones, 1984).

The effects of community noise may be evaluated by assessing the extent or degree of general annoyance among exposed individuals or the interference with different activities. The relation between annoyance and activity disturbances is not necessarily direct and there are examples of situations where a high level of activity disturbance is present although the extent of annoyance is low.

For aircraft noise, the most important activity interference seems to be interference with rest/recreation/watching television in contrast to road traffic noise where sleep disturbance is predominant. Whether this reflects a different distribution of the noise exposure over the 24 hours or if there is another reason is not known.

At present, a description of the activity interference of community noise can best be used as a supplement to the measurement of general annoyance, if not as its replacement.

7.9.3 Annoyance of Noise from Joint Sources

There are a wide range of sources of noise in the community. These include noise from industrial and commercial premises, construction machines, radios and televisions, air conditioning units and domestic pets.

In many situations these noises may only be transitory but in others they may continue for long periods or even be continuous. Unlike road traffic and aircraft noise general community noise can affect small groups or even individuals without affecting near neighbors.

General community noise is a frequent source of disturbance in the community and is a common source of complaint to governmental agencies. Most studies on the effects of railway noise show that, at the same equivalent continuous sound pressure level, railway noise gives rise to less annoyance than road-traffic noise (Miedema, 1987; Möhler, 1988). The most common metric used to assess the dose-response relationship has become the Leq based on the A-weighted sound level although the L_{10} measured against the L_{90} is also used (ISO 1999, 1990).

Modifications to the measured Leq value are often applied to improve the relationship for various noise characteristics and sources. The most common modifications ("penalty" factors) take into account factors such as the tonality, impulsiveness, low-frequency components, modulation, and the time of day. Often the existing background noise is also considered (Fields, 1993a).

Many noise sources have unique characteristics that require specific assessment procedures to determine the dose-response relationship for annoyance. To assess the noise from gunshots (at a shooting range) may require consideration of the peak sound levels, the number of peak noises, the time of day, and the frequency of use of the range. Similar considerations may be necessary to assess noise from pile-driving. Other construction noises may be appropriately assessed by considering its sound pressure level in conjunction with the duration of the noise.

Low frequency bass beats associated with modern music may require consideration of the sound pressure level relative to the background noise in the particular octaves of interest (e.g., 63 & 125 Hz).

In some situations noise measurements may not be a significant factor in determining a dose-response relationship. The length of time a dog barks at night may be the principal issue in determining the response to that noise. Other factors include the identification with the source or the person causing the noise, the particular needs of the recipient of the noise (e.g., sleep, rest), and the nature of the noise. An individual may also have very different responses to similar noises, for example, an individual may enjoy some music and be annoyed by other.

LAeq is now widely used in standards and legislation throughout the world as the basis on which to develop a dose-response relationship for community noise annoyance. It is particularly useful where the noise is steady and broadband. However, care must be taken when assessing most community noises to ensure that significant characteristics associated with the noise are considered. Measurement period must also reflect the noise being assessed to enable the dose-response relationship of the noise to be determined.

Often community noises appear jointly from several sources (Vos, 1992). It is possible to hear and also identify a specific noise among combined noises. Due to the analytic capacity of the auditory system, it is also possible to hear and identify sounds of a lower sound pressure level than another sound in the complex. The presence of environmental background noise, sometimes may make people mistake one community noise for another inside combined noises (B. Berglund, U. Berglund, & Lindvall, 1980).

Several models of loudness summation for community noises have been tested, for example, a vector summation model, a model assuming that the loudness of the masked constituent noises add arithmetically, and a simple dominance model stating that the total loudness equals the loudest of the component noises when heard alone (Powell, 1979; B. Berglund et al., 1981). An approximation for calculating “addition” of loudness based on characteristics of the hearing system (Zwicker & Fastl, 1986) leads to total loudness of two sounds in accordance with perceptual measurements. Other authors have discussed a larger number of possible models to predict annoyance due to combined sources (Taylor, 1982; Rice & Izumi, 1984; Diamond & Rice, 1987). Zwicker (1987) presents a procedure for calculating partially masked loudness based on ISO R532B (1966; ISO 532, 1975) using the knowledge of third-octave band levels of the masker (background noise) as well as of the sound in question.

Research on combined community noises has also been performed in surveys, including both source specific and total situation questions. The laboratory data on loudness perception (B. Berglund et al., 1981) indicate that a dominance model would possibly also predict the total annoyance of combined complex sounds (i.e., that the total annoyance equals the most annoying component noises or sources). This is questioned by Miedema (1987) who believes that a synergistic model cannot be ruled out for community annoyance reactions. Annoyance from a combination of sources is claimed to be often below the maximum of the ratings from the individual sources. However, in a meta-analysis of annoyance surveys, Fields (1993a) shows that for target noises in ambient noise, the annoyance of the target is mostly unaffected of the ambient noise. This would speak in favor of a dominance model.

The loudest or most annoying noise of a complex is not necessarily the noise of the highest sound pressure levels as measured alone. Loudness, as well as annoyance, are not directly related to sound pressure level (A-weighted or unweighted) but may mislead by as much as 380 % (Zwicker, 1987), corresponding to a factor of three in loudness or being equivalent to a difference of 15 dBA. Diamond and Walker (1986; see also Diamond & Rice, 1987) state that aircraft noise has more influence on “overall annoyance” than road traffic noise in areas exposed to both sources of noise. In addition, Miedema (1987) in an analysis has also suggested that when respondents are specifically asked to compare aircraft and road traffic noise they perceive aircraft noise to be more annoying. Very little research has dealt with the more realistic problem of temporal patterns of exchanging and overlapping sound events as an environmental exposure situation for evoking annoyance, however, an overview of issues in research on annoyance of such intermittent sounds has been given by B. Berglund, Harder and Preis (1994; cf. Berry, 1985).

7.9.4 Spontaneous Complaints, Protest Behavior and Residential Moving

Residents in a noise area have several ways of coping with annoyance. They may move to another area, make changes in the physical environment, try to change their judgments about the environment, or they may adopt other coping strategies, for example, make a redefinition of their personal needs. These processes may ultimately lead to consequences for the society. Therefore, noise problems should be observed as part of long-term sociological processes.

In a noisy residential area people have several ways of coping with the impacts of noise: they can make changes in the physical environment (e.g., by improving sound protection), try to change their judgments about the the environment or re-define their personal needs, try to influence the source by protest activities, or move out of the exposed area.

Among environmental issues, noise is one of the most frequent reasons for public protest (see Rohrmann, 1990b). Protest behavior occurs in various forms, for example:

(a) complaints by letters, phone calls or personal visits to authorities
(b) formation of citizen movements
(c) participation in rallies/demonstrations, and
(d) running judicial processes.

Commonly only 5 to 10% of residents exposed to noise actually complain or participate in any related activity. Also, because of the strong influence of psychosocial factors (such as education, self-confidence, political orientation), the number of complaints is poorly correlated to noise exposure (cf. e.g., McKennell & Hunt, 1961; McKennell, 1963, 1980; TRACOR 1971; Avery 1982; Schümer & Zeichart, 1989). Altogether, complaints may be a relevant indicator of the existence of noise problems in a community, yet not necessarily of the intensity of the problems. The latter needs to be addressed by representative epidemiological survey studies (Lindvall & Radford, 1973; Avery, 1982).

Since noise is a serious impairment of environmental quality, noise should be relevant for people's decisions about their residency. Two issues have been investigated: whether noise exposure leads to moving, and whether noise exposure is considered in residential choice (Michelson, 1980; Rohrmann, 1991). The field studies available so far (e.g., Schümer-Kohrs & Schümer, 1974; Rohrmann, 1991) indicate that significant weight is put on the noise exposure condition among the principal considerations whereas noise exposure has only moderate influence on actual moving or housing decisions. This is believed to be due to predominant social and economic factors, for example, financial, occupational or family constraints. However, there is also evidence that people may underestimate, considerably, either the impacts of noise exposure, or their coping ability when considering and selecting a new residence. By enhancing environmental sensitivity and, in particular, noise awareness of movers, many cases of residential dissatisfaction might be avoided.

7.9.5 Annoyance Before and After Intervention

Several studies have dealt with the methodological problem of determining the change in annoyance or dissatisfaction after remedial actions. Sometimes a change in noise level produces a change in reaction which is much greater than would be predicted from the change in noise exposure alone (Langdon & Griffiths, 1982; A.L. Brown, Hall, & Kyle-Little, 1985; Raw & Griffiths, 1985; Griffiths & Raw, 1986, 1989). With decreased noise exposures a "virtual", added, long-lasting decrease in annoyance may take place corresponding to about 10 dB for road traffic and 5 dB for aircraft noise (LAeq). There is little evidence for an adaptation or habituation effect (N.D. Weinstein, 1982), rather expectations among the survey respondents formed by the change in noise exposure itself as well as repeated questioning may produce the substantially reduced reaction.

The influence of attitudes to the noise source (Job, 1988a, 1988b) and the formation of response criteria with regard to annoyance have been pointed out as current areas of concern (B. Berglund, U. Berglund, & Lindvall, 1975b, 1975c; A.L. Brown, 1987). Furthermore, residents may deliberately "reward" relevant authorities for reduced noise by showing greatly reduced reaction, or "punish" decisions resulting in increased noise by showing greatly increased reaction (Job, 1988b).

People can be protected against noise annoyance, for example, by insulation of the house. However, the insulation has to be rather heavy to produce beneficial effects equal to or above what is to be expected based on a "steady state" dose-effect relationship (Bitter & Willigers, 1980). In some cases people may react to noise (in terms of annoyance) "as if they are standing in the doorway". The outside and the inside situation may then be of about equal importance in determining annoyance. Indeed Peeters, de Jong and Tukker (1981), in studying railway noise, found annoyance to be virtually independent of the insulation qualities of houses. People do not always use the potential of their sound insulation measures to the full. For example, in the Netherlands, most people prefer sleeping with open windows (ranging from 80-90 % on average in the summer to 60-65 % in the winter). Reasons for disliking the windows closed are: feeling the loss of freedom to behave as preferred, bedroom-odors, and too-high temperature (especially at night). DORA (1980) registered around the airports of Heathrow and Gatwick 66 % of people sleeping with windows open. No difference in behavior was found between people living in extra-insulated and not extra-insulated houses. Taylor (1984), using path-analysis on survey results, made it plausible that windows are usually not shut before going to bed except when (sleep) disturbances occur. This might explain the odd finding that people sleeping with closed windows (maybe forced to) sometimes report more annoyance than people who do not.

7.9.6 Dose Response Relations for Annoyance

Characteristics related to the disturbance and annoyance potency of long-term noise exposure include the manner in which the sound level of noise events vary with time (e.g., the distribution of noise events over a 24-h period). Considerable effort has been devoted to the search for an acoustic index of chronic noise exposure. The major requirements of such an index are that it should be well correlated with human reactions and that it should be convenient to measure.

7.9.6.1 Measurement of community annoyance

Abatement programs of ambient noise are often based on criteria involving measurement of annoyance. The term annoyance is used differently by noise researchers, and its meaning is discussed by several authors (Lindvall & Radford, 1972; Altena, 1987, 1990). In search for dose-response relationships it has been obvious that psychological concepts such as loudness, noisiness, or annoyance may have different relationships to the physical descriptors of the noise. B. Berglund, U. Berglund and Lindvall (1975a) have shown that observers are able to differentiate between different psychological attributes of aircraft noise in a laboratory setting. For example, in general aircraft noise was judged to be more annoying than noisy and more noisy than loud.

In social surveys dealing with community response to environmental noise, annoyance measures have been the primary response variable (Gunn, Petterson, Cornog, Klaus, & Connor, 1975). In some cases the respondent is

simply asked about his or her annoyance ratings on a (numerical) category scale. In other cases the respondents are asked about the noise interference with other activities. For these both cases, the individual annoyance scores are then quite arbitrarily added together to form an “overall annoyance score”. One large problem in community noise surveys is the high variability found in measured annoyance at any one noise level. Although a part of such variability may be due to random measurement errors, much can also be associated with acoustical, situa-
tional and psychological factors (Gunn, 1987; Langdon, 1987; Job, 1988a; Fields, 1993b).

Many community noise surveys have been in the form of cross-sectional studies. At least three types of problems are associated with these kinds of study. The first problem is that data obtained from cross-sectional studies yield only correlational data from which causal inference is highly uncertain. The second problem concerns the adequacy of predicting the reactions of previously unexposed populations based on the reactions of long-term survivors in highly noise-impacted airport areas of the community. The third problem is that data seldom has been cross-validated. Since Schultz (1978; see also Fidell, Barber, & Schultz, 1991) compiled his dose-response relationship, which is considered to be valid for all kinds of transportation noise (car, train, aircraft), studies have been performed to either reject or verify this idea (Kryter, 1982, 1983; Miedema, 1993; Bradley, 1994). Studies show both more and less intense noise disturbances than shown in Schultz’s relationship which refers to percentages highly annoyed persons.

The difficulties encountered in estimating noise source differences have been outlined by Fields and Walker (1982; see also Rohrmann 1983a, 1983b ,1986). For estimation of the degree of measurement error in both noise and reaction, see Job (1988a). In comparing different survey data several issues must be considered (F.L. Hall, 1984):

(1) Are the questionnaires used in field studies sufficiently precise to identify and compare different perceptions of the noise from the various sources?

(2) Are the noise metrics in current use sufficiently precise to characterize the different acoustical and temporal characteristics of the noises?

(3) Is the variation in the results simply due to random sources or measurement error?

A central issue in noise abatement considerations is to identify why some noises are more annoying than others. Some noises are primarily annoying because of their sound pressure level (e.g., aircraft noise), whereas others are primarily annoying because of their temporal pattern (e.g., noise from a typewriter), (B. Berglund, U. Berglund, & Lindvall, 1976). Still others are strong because they are intrusive (B. Berglund, Preis, & Rankin, 1990). When closely spaced tones are combined with noise, perceived annoyance increases (Hellman, 1985; Hellman & Zwicker, 1989). The reason may be due to a perceived roughness of the combined sound. It is reasonable to assume that the concept of annoyance is more affected by factors external to the physical descriptors of noise (e.g., individual factors, attitude towards the noise source, activity disturbance, etc.) than is the concept of loudness.

Many authors suggest that loudness is the dominant factor in producing annoyance (B. Berglund, U. Berglund, & Lindvall, 1975a; von Brennecke & Remmers, 1983; Fastl, 1985; Fastl, Markus, & Nitsche, 1985; Fastl & Yamada, 1986; Hellman, 1982; Hellman, 1985; Namba & Kuwano, 1984; Schick, 1981; Stassen, 1980; Weber & Mellert, 1978) but other factors such as intrusiveness and information content are often involved (Preis & B. Berglund, 1994). It has been suggested that annoyance of strongly time-variable sounds might be estimated from a percentile of loudness (Berry & Zwicker, 1986).

A model for human response to noise has been proposed by Gunn (1987). It takes into consideration all of the contextual and other factors which are important in determining how any individual will react to a specifiable noise in a given situation or context. The model was developed to reveal measurable changes within communities exposed to aircraft noise, and is based on the premise that individuals will attempt to reduce, avoid, or eliminate stress in their lives.

The stress reduction model postulates that annoyance response to noise is mediated by three primary factors:

(1) the inherent unpleasant characteristics of the noise;

(2 the meaning associated with the noise source; and,

(3) the interference with ongoing activities (Lindvall & Radford, 1973; Borsky, 1980).

Interference with television viewing (involving visual and auditory perception) is a major aircraft noise related problem (Galloway & Bishop 1970), and different auditory functions relating aircraft noise exposure to annoyance responses have been found for persons engaged in different perceptual activities (Gunn, Shigehisa, J.L. Fletcher, & Shepherd, 1981). Furthermore, annoyance may grow differently than loudness with changes in noise spectrum and sound pressure level. In accordance with speech masking theories (G.A. Miller, 1947), the maximum annoyance reduction to aircraft noise occurred when a given amount of energy was removed from octave bands in the frequency range 800-1,600 Hz (Gunn, Shigehisa, & Shepherd, 1977).

While it has been found that annoyance generally increases with sound pressure level, it has also been found that communities vary considerably in their reaction to the same sound level. The average of the standard deviation of these differences has been found to be the equivalent of a 6 dB difference in sound pressure level (Fields, 1983). Differences between reactions in different cities may be as great as the equivalent of a 15 dB difference. The sources of these differences are poorly understood. One implication of such differences is that reliable findings about annoyance can be established only if large numbers of locations are studied or if the findings from several surveys can be compared.

Annoyance is generally related to the direct effects of noise on various activities, such as interference with conversation, mental concentration, rest, or recreation. The degree of physical exposure as well as intervening psychosocial variables (moderators) determine the occurrence and extent of the annoyance response. Examples of such factors are the level of noise, its spectral, temporal, and impulsive characteristics, information conveyed by the noise, fear of health/safety impacts, noise sensitivity, and attitudes towards the source of the noise (e.g., McKennell & Hunt, 1961, McKennel, 1980; Cederlöf, E. Jonsson, & Sörensen, 1967; Rohrmann, Schümer, Schümer-Kohrs, Finke, & Guski, 1973; Finke, Guski, & Rohrmann, 1980; Job, 1988a; Fields, 1990). All these variables must be measured in experimental or epidemiological studies, in order to arrive at an appropriate judgment concerning annoyance effects (Borsky, 1972; Lindvall & Radford, 1973; Rohrmann, 1984; Koelega, 1987). Also, without a thorough knowledge about moderators, the possible effectiveness of acoustical noise abatement measures is hard to evaluate.

7.9.6.2 Aircraft noise

The noise of aircraft can arise during take-off and landing. Noise can also arise, i.a., from ground running, reverse thrust used on landings, and, in the case of training airfields, the regular flyover of aircraft. Helicopters are a particular type of aircraft and have a different dose-response relationship to fixed wing aircraft.

An early general noise exposure index was the Composite Noise Rating (CNR) devised by Rosenblith and K.N. Stevens (1953) for assessing environmental noise nuisance. Initially, this index was quite elaborate, accounting in a semiquantitative way for average sound level, discrete frequencies, impulsiveness, repetitiveness, and background noise. Some psychosocial factors were also taken into account by considering time of day (on the assumption that people are more noise-sensitive at night) and the history of the previous noise exposure of the community. It was later modified in the light of experience.

Since that time there have been many studies (e.g., Job, 1988a) on the dose-response relationships. These have identified a range of non-acoustic issues such as fear of aircraft crashing, and loss of privacy (especially for helicopters) as being significant.

All indices involve specially weighted measurements of average aircraft sound levels expressed, for example, in dBA, dB(PN), or dB(EPN). Some take into account the duration of the sound, others do not. In most cases, the influence of some psychosocial factors is accounted for, directly or indirectly. Basically, the differences in various indices for the estimation of mean perceived magnitude are small (Botsford, 1969; Young & Peterson, 1969; Ollerhead, 1973).

7.9.6.3 Road traffic noise

The traffic noise index (TNI) was developed from the results of a social survey in London (Griffiths & Langdon, 1968). It was based on the weighted combination of the sound levels (in dBA exceeded for 10 %, 50 %, and 90 % of the time) according to the formula:

$$TNI = L_{50} + 4\,(L_{10} - L_{90}) \qquad (8)$$

This index reflects the conclusion that traffic noise annoyance depends not only upon the average or typical sound pressure level (L_{50}) but also upon the magnitude of the fluctuation (L_{10} - L_{90}). However, further investigation revealed that, because of the practical difficulties of predicting L_{90} with an adequate degree of confidence, the value of TNI was susceptible to large errors. For example, TNI-values decrease when the traffic increases. Thus, TNI was subsequently rejected in favor of L_{10} for traffic noise compensation regulations (UK Statutory Instrument, 1975), even though its correlation with annoyance was shown to be inferior to that of TNI in the original survey.

Because of the high correlation between different indices that are sensitive to peak levels in the noise-time history, it may safely be assumed that any such index will predict traffic noise annoyance reactions with close to equal reliability. Evidence of the importance of maximum sound pressure levels comes from investigations in England (Langdon, 1976) and Sweden (Rylander, Sörensen, & Kajland, 1976) in which the extent of annoyance was found to be well-correlated with maximum sound pressure levels generated by heavy vehicles. The correlation between Leq and the extent of annoyance was relatively low in the second of these studies, however, a high correlation was found for urban traffic noise in population studies by J. Lang (1965).

A re-evaluation of available data on traffic-noise exposure and annoyance has recently been carried out by a working group of the ISO (Sandberg, 1993). Several existing and newly-proposed indices, mostly derived from Leq, were correlated with subjective response and though it was recognized that insufficient data were available to draw a firm conclusion, it was recommended, that, at present, Leq (as described in ISO 1996R (1971; replaced by ISO 1996/1, 1982) should be used for the assessment of road traffic noise.

7.9.6.4 Low frequency noise and vibration

Low frequency noise is common as background noise in urban environments and as an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and indoor ventilation and air conditioning units (Tempest, 1976; Leventhall, 1988). The effects of low-frequency noise are of particular concern because of its pervasiveness due to numerous sources, efficient propagation and reduced efficacy of many structures (dwellings, walls, and hearing protection) in attenuating low frequency noise compared with other noise (B. Berglund, Hassmén, & Job, 1994).

Intense low frequency noise may produce clear symptoms including respiratory impairment and aural pain (von Gierke & C.W. Nixon, 1976; see also von Békèsy, 1960). Although the effects of lower intensities of low frequency noise are difficult to establish for methodological reasons, evidence suggests that a number of adverse effects of noise in general may be greater for low frequency noise than for the same noise energy in higher frequencies: loudness judgments and annoyance reactions are greater for low frequency noise than other noises for equal sound pressure level regardless of which weighting scheme is employed (Goldstein, 1994); annoyance is exacerbated by rattle or vibration induced by low frequency noise; speech intelligibility may be reduced more by low frequency noise than other noises (except those in the frequency range of speech itself because of the upward spread of masking) (Pickett, 1959; Loeb, 1986).

Noises with low-frequency components contribute to annoyance in at least three different ways (Lindberg & Backteman, 1988):

(1) A feeling of static pressure is produced by low-frequency components if they reach levels and frequencies above a certain threshold. Such “ear-pressure” may be produced, for example, by riding in a car for at least half a minute with the window slightly opened so constituting a Helmholtz resonator.

(2) Low-frequencies produce periodic masking effects in medium and higher frequencies. Speech sounds are strongly amplitude modulated, and conversation is disturbed although speech remains intelligible. The effect can be measured quantitatively by so-called masking-period patterns.

(3) Strong low-frequency components produced by aircraft may rattle doors, windows, and other contents of houses. These secondary physical sound sources may be much more annoying than the original primary low frequency component.

The general use of the A-weighting filter attenuates the low frequencies so that the A-weighted sound pressure level does not reflect the true impact of the noise load. A common practice is, therefore, to measure both A-weighted and C-weighted sound pressure levels, and by comparison identify the potential impact of low-frequencies in exposures.

With various sources, such as heavy trucks and trains or particular industrial plants, both noise and vibration effects occur. People are disturbed and annoyed by both factors; they also tend to “mix up” these effects or to perceive vibration as noise (Kryter, 1985, 1994; Griffin, 1990; Howarth & Griffin, 1990; Meloni & Krüger, 1990; Kastka & Paulsen, 1991).

Although firm scientific evidence is lacking, some consider by experience, that noise with a high proportion of low frequency components in some instances may be better tolerated by people than noises with a high proportion of high frequency components. However, comparison of socioacoustic survey results from different noise sources supports a greater reaction (for equal loudness) to sources with more low frequency noise. Reaction to aircraft noise is, thus, generally greater than reaction to road noise and this difference has been identified in direct comparison (Hall, Birnie, Tayler, & Palmer, 1981).

7.9.6.5 Impulsive noise

Impulsive noise refers to noise with a sudden onset and termination. Studies of community reaction to artillery ranges (Bullen, Hede, & Job, 1991), rifle ranges (Sörensen & Magnusson, 1979; Hede & Bullen, 1982), drop forging (Seshagiri, 1979), and quarry blasting (Fidell, Horonjeff, Schultz, & Teffeteller, 1983) have shown community reactions to be somewhat different for impulsive noise than for other noises. While there are similarities such as reasonable prediction of reaction by equal energy noise indices (see Bullen & Job, 1985; Bullen, Hede & Job, 1991), and the influence of attitude and noise sensitivity, important differences exist. First, the extent of prediction of individual reaction to noise exposure is lower for impulsive noises than for other sources and this does not appear to be due to less accurate measurement of noise exposure (Job, 1988a). Second, community reaction is substantially higher for impulsive sources than for non-impulsive noises. For example, Bullen, Hede and Job (1991) found a dose-response function which indicated that the level of artillery noise required to produce a given level of reaction was about 30 dBA lower than the level of intermittent noise which produces a similar reaction. In terms of C-weighted Leq the difference was somewhat reduced (see also Schomer, 1981). These differences between reactions to impulsive and non-impulsive noise are poorly understood.

Figure 8. Normal distribution of annoyance scores (Ollerhead, 1973).

7.9.6.6 Dose-response relationship

The direct correlation between long-term noise exposure and annoyance has been studied for various kinds of noise exposure. The numerous composite noise indices that have emerged from these studies have been attempts to improve this correlation, by taking intoaccount various factors including: time of day (day, evening, night), noise source (e.g., aircraft, road traffic, industrial source) and type of neighborhood (e.g., rural, suburban, commercial).

Regardless of how the dose scale is derived, the main technique for evaluating its validity is through use of the social survey. Such surveys (e.g., McKennell, 1963, 1980; MIL Research Ltd, 1971; TRACOR, 1971; Finke, Guski, & Rohrmann, 1980; Job, 1988a) have shown that the correlation coefficient between noise exposure and average response is relatively high (>0.8) implying that the noise scales are useful predictors of average reaction. Sound pressure levels typically explain only 10 to 30% of the variability in annoyance responses. Intersubject variability is high, both with respect to exposure and reaction, and the correlation coefficient between noise exposure and individual annoyance is low (<0.5).

Much of the variation between individuals can be attributed to sociopsychological factors. In a study of aircraft noise (TRACOR, 1971), the most important of the factors were fear of crashes, general noise susceptibility, ability to adapt to noise, opinions about the importance of the aircraft operations, and belief that the noise could be better controlled.

Figure 9. Percentage of respondents highly annoyed as a function of exposure to general transportation noise (day-night average sound level in dBA Ldn). Least squares quadratic fit to 453 data points of 27 epidemiological community surveys. The third-order polynomial fitting function of 161 of the data points by Schultz (1978) is also shown (double line). (From Fidell, Barber, & Schultz, 1991).

The interrelationship between these factors is very complex. Even the direction of the causality is not clear: does fear of crashes increase noise annoyance or vice versa? The multivariate statistical analyses performed in some studies are not adequate to resolve such questions.

By comparing results of noise annoyance surveys around major airports, it has been found that variation between the reactions of individuals is very similar from place to place and from time to time (Alexandre, 1970; Ollerhead, 1973; Rylander & Sörensen, 1974). Regardless of how the reaction is measured, people express similar degrees of annoyance in relation to similar ranges of noise exposure. However, the total range is considerable. Fig. 8 shows the cumulative distribution of annoyed people at London Heathrow Airport as a function of noise exposure measured in NNI (Ollerhead, 1973). The different curves represent different annoyance levels, and each is a cumulative Gaussian distribution with a standard deviation of 20 NNI. Comparison of these curves with similar data from other surveys suggests that they would be valid for any major international airport with about 20 % of its aircraft movements occurring at night.

Attempts have been made to cluster epidemiological data from the large number of surveys which have been conducted in order to study the association between prevalence of reported annoyance and noise exposure from various sources. A relationship was indicated by Schultz (1978) on the basis of data from a dozen community questionnaire surveys. A third-order polynomial function was found to describe well the relationship. However, the data points scatter much so the value of the curve for prediction purposes in the individual case must be questioned. An updating of the Schultz curve has been made comprising an additional 15 studies, Fig. 9 (Fidell, Barber, & Schultz, 1991).

The noise exposure scale in Fig. 9 is day-night average sound level (Ldn expressed in dBA). Although the number of data points from which the new relationship was inferred more than tripled, the 1978 relationship still provides a reasonable fit to the data but so does also a second-order function. Despite the large spread in data points (which partly may be associated with the disparity in the meaning and measurement of “highly” annoyed as well as in the exposure assessment), Fig. 9 indicates that a level of Ldn < 55 dB will cause relatively little annoyance in many cases. Care is deemed necessary to avoid using these relationships outside their intended ranges (Fidell, Barber, & Schultz, 1991). It is common sense that the functions must be asymptotic to values of the prevalence of annoyance in the vicinity of 0% and 100%.

Since Schultz (1978) published his single dose-response relationship for annoyance of transportation noise, an intense debate about the adequate description of the curve has taken place. For example a refined description was proposed by Kryter (1982, 1983) and commented on by Schultz (1982b). In addition to the updating by Fidell, Barber and Schultz (1991; see also Fields, 1994), Miedema (1993; see also Bradley, 1993) reanalyzed compiled data from a number of studies involving mobile (aircraft, highway and other road traffic and railway noise) as well as stationary sources (impulse noise as well as non-impulse). For equal Ldn, aircraft noise and highway noise are more annoying than other road traffic noise, which in turn is more annoying than railway noise (trains, trams). Especially at low levels, impulse noise is more annoying than any transportation noise. Miedema (1993) proposes a system for rating adverse effects due to noise immissions; the system being based on the compiled dose-response functions for various noise sources.

7.9.6.7 Weighting of day-and-night noise exposures

Acoustically similar noise environments are often assumed to cause more annoyance in residential areas during the evening or night hours than they would during the daytime. A nighttime weighting is therefore included in some noise indexes, such as Ldn. An analysis of ten studies with a total of 22,000 respondents found some evidence that evening and nighttime noise may have a somewhat greater impact on annoyance (Fields, 1985, 1986). However, the size of this difference cannot be specified with any accuracy.

In many cumulative noise indices, such as the Ldn and Noise Exposure Forecast (NEF), noise at nighttime is weighted 10 dB more than noise at daytime. The noise indexes that also take annoyance at evening time into consideration (usually between 7 and 10 p.m.), add 5 dB to the measured sound pressure levels.

When the weight factor was introduced in Ldn, the following three reasons for weighting noise at night-time were advocated:

(1) Community noise is perceived as more annoying during nighttime than during daytime.

(2) The need for a low noise level for sleep at night motivates a further reduction, because the background noise level is ordinarily reduced during nighttime.

(3) The lower indoor activity during nighttime contributes to a lower noise level.

Many studies verify reasons 2 and 3, that is, at low levels of background noise the annoyance from the noise source increases. Although a relationship between daytime noise exposure and night sleep quality has been suggested (e.g., Blois, Debilly, & Mouret, 1980), it has not been possible to empirically show how much noise at nighttime should be weighted in relation to noise at daytime. In a sociological study close to airfields in Australia, Bullen and Hede (1983) found that people estimate the need for non-interference of noise to be most important between 6 and 9 p.m.

7.9.7 The Importance of Number of Noise Events and Sound Levels

Laboratory and field studies on annoyance (and sleep) after exposure to noise from aircraft, road traffic, train, shooting ranges, and artillery ranges show:

(1) The relationship between effects and the equal energy measure is relatively weak particularly for sleep effects.

(2) Personal perceptions of the exposure situation as well as general annoyance and sleep disturbance are highly related to the sound pressure level from the noisiest events (trucks, noisiest aircraft type, etc.).

(3) The number of events influences the extent of annoyance and the sleep disturbance; for annoyance there is seemingly a threshold above which an increase in the number of events does not increase the extent of annoyance.

A large number of field surveys have examined the impact of the number of noise events on annoyance (Rylander, Björkman, Åhrlin, & K. Berglund, 1980; Fields, 1984; Bullen & Hede, 1986; Fields & Powell, 1985; Björkman, 1991). The survey data do not provide sufficiently accurate results to conclusively prove that Leq is preferable to other competing noise metrics. In an analysis of the data from eight surveys it was found that the best estimates of the relative effect of sound level and number of events do not reject the trade-off implied by Leq, but are also consistent with a weaker effect for the number of noise events (Fields, 1984). Consistent with a predictive role for number of events as well as Leq, studies have reported that in regression analysis the number of events adds to the prediction of annoyance by equal energy units (Bullen & Hede, 1986; Bullen, Hede, & Job, 1991). Further studies are not likely to yield improved estimates unless there are important developments in the annoyance study methodology.

Commonly, the noise events are added to the prevalence of annoyance according to the principle of equal energy. The influence of the number of noise events (n) on percentage of annoyed subjects (%s) may be expressed by the formula (LA is here A-weighted sound level in dB):

$$\%s = LA + k \log (n) \quad (9)$$

When the noise events are added according to the principle of equal energy, the value of k is 10 in Equation 6. However, there are often large variations; the value of k can vary within -3.7 to +23.8 depending on the type of noise event index being used (Fields, 1984).

The effect of the number of noise events on annoyance has been extensively researched by Rylander and coworkers (Rylander, Sjöstedt, & Björkman, 1977; Rylander et al., 1980; Björkman, 1988, 1991). When the number of noise events per hour increases, the annoyance increases initially and, after leveling off, seemingly it starts even to decrease. Similarly, laboratory studies on road traffic noise show that annoyance is influenced by the sound level in Leq and the number of vehicle passages (Rasmussen, 1979; Labiale, 1983) but do not seem to confirm the tendency of an inverse-U relation reported by the Rylander group. Fields (1984) has advocated other interpretations of the aircraft annoyance data, that form the basis of the model proposed by Rylander and co-workers. In studies of annoyance caused by low frequency sounds from artillery fire, Vos (1992) found that respondents experienced less annoyance the more the shooting was restricted to a smaller number of days or evenings per year, up to a point.

Little information is available about reactions to very low numbers of noise events, such as would be experienced near very small airports or near some military operation areas. In an experimental study of as few as one helicopter noise event per day there was some weak evidence that reactions were consistent with Leq (Fields & Powell, 1985). However, there is virtually no evidence available about how people react to infrequent (less than once a day) or irregular high level noise events. Leq may not be at all appropriate in such situations.

7.9.8 Relationship between Annoyance and Physiological Effects

The feeling of annoyance in a noise exposed population is an adverse effect by itself. However, there are few studies that have researched a potential relationship between measurable physiological effects and self-reported annoyance. Arvidsson and Lindvall (1978), in a simulated laboratory experiment (traffic noise, 85 dB LAeq), showed an association between reported feelings of annoyance, performance efficiency, and the subjects' perceived influence of noise on their performance. But, they found that simple measures of physiological arousal (urine catecholamines) are not adequate predictors of self-reported noise annoyance. Neus, Ruddel and Schulte (1983) investigated traffic noise annoyance in a cross-sectional epidemiological study. They observed an association between hypertension and self-reported annoyance for moderate noise loads, but not for high loads.

7.9.9 Summary

The annoyance-inducing capacity of a noise depends mainly upon its intensity and spectral characteristics, and variations of these with time. However, annoyance reactions are sensitive to many nonacoustic factors of a social, psychological, or economic nature and there are considerable differences in individual reactions to the same noise. Furthermore, community annoyance varies with activity (speech communication, relaxation, listening to radio and TV, etc.).

Annoyance is affected by the equivalent sound level, the highest sound level of a noise event, the number of such events, and the time of the day. The method of combining these parameters of noise exposure to an indicator for the observed annoyance level has been extensively studied. The data are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the Leq index, and which in many cases is a fairly acceptable approximation. However, there is a growing concern that all the parameters mentioned should be assessed in noise exposure investigations, at least in the complex cases. The reason for this is that the nonacoustic factors are known to interfer in annoyance and, therefore, simple measures such as LAeq may only have face validity.

It should be noted that a large proportion of low frequency components in the noise may increase annoyance considerably. Where prominent low-frequency components are present, they should be assessed.

8 SOCIETAL ECONOMIC COSTS OF COMMUNITY NOISE

8.1 Introduction

No economical models have been developed that may be used for calculating the total costs for the society at large caused by community noise exposure. Decisions concerning governmental noise policies are often based on economic models, such as cost-benefit or cost-effectiveness analyses.

In cost-benefit analysis, costs and benefits are compared in monetary terms. Typically, benefits are defined in terms of the damages that are avoided and cash values are attributed to these damages. For this reason, knowledge from social and behavioral studies of noise is difficult to transform so that it easily may be incorporated in cost-benefit analyses. To become complete, cost-benefit analyses would need to consider in monetary terms the societal costs for noise-induced illnesses, disabilities, as well as the losses in productivity. In addition to these primary costs, secondary costs are involved that are related to a further deterioration of life quality, for instance in the form of discomfort and annoyance caused by noise exposure. In a short term perspective, the consequences of an increased noise pollution are usually lowered market values of real estate, population segregation, and general deterioration of residential areas.

Often the concept “social cost” is adopted to define the adverse environmental impacts of an activity. “Total social cost” is a quantitative construct expressing the impact of community noise on economic activity (Quinet, 1990). Ideally one would like to express the expenditure, inconveniences and drawbacks of community noise in a single monetized figure. Social cost can be defined in various ways (Quinet, 1990):

(a) a narrow definition would be the actual remedial expenditure recorded in the national accounts for noise abatement;

(b) a frequently used definition would include not only the remedial costs but also the calculated permanent damage;

(c) a wider but still debatable definition would be the sum of consumers’ and non-consumers’ marginal willingness to pay to reduce noise pollution.

The social cost due to noise has been evaluted mainly with respect to road transport. Kanafani (1983) has identified two economic effects: the expenditure on protection and the cost of damage. The social cost of transport noise in studies from various countries has been summarized by Quinet (1990) to be around 0.1 % of the Gross National Product (GNP); the range being 0.06-1.0 %. Roughly 90-93 % of the costs would be due to road traffic and 7-10 % due to rail traffic (CETUR, 1982; Netherlands Environment Ministry, 1985). With respect to the social costs for all noise nuisance, Wicke (1987) estimated that in Germany this cost was around 2 % of the GNP; about 0.2 % being productivity losses and 1.9 % decreases in property values.

As an alternative to cost benefit analysis, the cost-effectiveness analysis aims at finding the most effective measures at the least costs. The definition of effectiveness may pose a problem. Basically there are two ways to measure the effectiveness of a noise abatement policy (Lambert & Vallet, 1994):

(a) by estimating the difference in the number of people “highly annoyed” by noise before and after mitigation and relating the potential difference in cost of the remedial actions, and

(b) by estimating the variation in exposure of the whole population to noise before and after mitigation in terms of cost of remedial actions. In this case the estimate should be based on an exposure indicator combined with an empirical or assumed exposure-response function, for example, the one for loudness.

8.2 Expenditure on Protection

The expenditures against noise pollution include: at-source abatement costs, community protection, for example, by screens and vegetation, and private protection costs, for example, by sound insulating windows.

The cost for abatement measures has been studied for road transportation noise. If the aim is to achieve a reduction in emission levels to 75 dBA for light vehicles and 80 dBA for heavy freight vehicles, the increase in price is calculated to be <3 % and 7 %, respectively (Quinet 1990). The gain would be 4-10 dBA. OECD (1982) estimated that a 5 % increase in costs for heavy freight vehicles would reduce emission levels to 80 dBA, and a 2 % increase in costs would reduce coach emission levels by 10 dBA.

8.3 The Cost of Damage

The calculated subsisting damage caused by noise pollution include productivity losses, health care costs, effects on property values, and loss of psychological wellbeing.

Productivity losses may be caused by the exposed persons' inability to concentrate, by communication difficulties at work, or by fatigue due to lack of sleep or inadequate rest outside work. Only a few investigations have been directed to assess productivity loss due to noise and the study designs have been critizised. In Germany the productivity losses due to noise from many sources, not just transportation, was estimated to be 0.2 % of the GNP (Wicke, 1987).

Health care to remedy physiological and psychological effects may be an important cost of damage. However, it is still dubious to assess health care costs due to community noise specifically since noise as a cause cannot be isolated from other factors (e.g., air pollution from traffic).

Noise exposure reduces land values, but complex analytic techniques are needed to separate noise effects from those of location and transportation. The quantitative studies conducted show varying figures for loss of property values due to community noise (Opschoor, 1986; Kanafani, 1983; Nelson, 1987; Pearce, Barde, & Lambert, 1984; Quinet, 1990; for an overview, see Lambert & Vallet, 1994). The decrease in housing values is represented by the change in percentage of prices paid for buildings per unit increase in noise exposure. It also expresses the sensitivity to noise of the property market expressed in terms of marginal rates of depreciation per decibel. Seemingly the rate of depriciation has changed significantly over time (Lambert & Vallet, 1994). During the 1960s the rate of depreciaton was negligible or near zero but the research methods were not very accurate. During the 1970s, the fall in housing value due to noise exposure was approximately 0.3 to 0.8 % per decibel, and during the 1980s the rate of depreciation has increased to approximately 1 % per decibel. The exposure threshold from which the cost is assessed varies often between 55 and 65 dBA, which may result in a variation by a factor of 3 in the estimated total depriciation of all housing. The fact that community noise reduces land value stresses the importance of land planning. Proper planning can lead to long range increase in value for industrial property.

Loss of psychological wellbeing is an important cost of damage, assuming that silence is generally preferred to noise. However, it seems practically impossible to set a direct monetary price on such a cost. It might indirectly and partly be reflected in the willingness of the exposed individual to pay for noise reduction and by damages awarded by courts to people. Furthermore, cost-effectiveness may be estimated, for example, by the reduction in the number of very annoyed people per million of ECU invested annually (Nielsen & Solberg, 1988), or by the percentage of the population exposed to road traffic noise at certain sound pressure levels when alternative noise abatement policies are applied (Lambert, 1990).

8.4 Individual Willingness to Pay for Noise Reduction

Quite often citizens must make judgments concerning the costs and advantages of a new factory, airport, or motorway, and need to understand the noise consequences if they are to make an informed decision. One approach to express the cost of community noise in a monetized figure, although still debatable, is to investigate the citizens' willingness to pay to reduce noise pollution (Walters, 1975; Starkie & D. Johnson, 1975; Langdon, 1978). Although based on different methods, the values people report they are prepared to pay to reduce road traffic noise are in the range 1.6-5 % of annual per capita income and to reduce aircraft noise maybe 2-7 %. A study in Sweden (Kihlman, Wibe & S.V. Johansson, 1993) indicates that tenants in residential buildings exposed to road traffic noise higher than 70 dB LAeq outdoors would be willing to pay an extra cost for sound proof windows of around 1500 ECU per window. To achieve a fully sound insulated dwelling, free from excessive noise from traffic, ventilation system, neighbours, etc., the tenants reported themselves willing to accept an increase in rent costs by 1-3.3 %. Weinberger (1992) in studying the costs of nuisance and noise pollution found that the average individual consent of monthly rent ranged from 0.83 ECU per dBA for low sound exposure conditions (<43 dB LAeq) to 1.24 ECU per dBA for high exposure conditions (>75 dB LAeq). The annual cost of traffic noise in Germany was estimated to be 7.8 to 9.6 billion ECU of which sum, road traffic noise was 70 %, railway noise 28 % and aircraft noise 2 %. [Please note that this distribution of costs reflects the extensity of noise pollution of various sources rather than severity of adverse health effects in a population.] In comparison, the estimated annual expenditure on noise abatement was only 18 % of the needs revealed.

8.5 Summary

The application of cost-benefit analysis to community noise is extremely complex and should be used in decision-making only with great caution. As rules of the thumb, the following valuations may be made. However, they are accompanied by a strong warning that the resulting values are imprecise and may not be universally representative, and that large margins of uncertainty should be allowed. The social costs for all noise nuisance have been estimated for one industrilized country (Germany) to be around 2 % of the GNP. The social costs of transport noise in studies from various countries have been summarized to be approximately 0.1 % of the GNP. Roughly 90 % of these costs would be due to road traffic. Seemingly, the rate of depreciation in housing values due to noise exposure has increased significantly over time.

9 MEASUREMENTS OF EXPOSURE

9.1 General Aspects

There are several problems associated with the assessment of a person's noise exposure over a period of time. During each day, a person is exposed to a variety of environmental noises at home, in the general environment, and at work. This pattern might change from day to day or year to year. The noise exposure pattern and dose change with age, lifestyle, occupation, and many other factors. Special regard must be paid to the so-called sensitive groups as these may react negatively to a lower sound pressure level of noise than others. Thus, estimates of total noise exposure are always very crude approximations. Particularly, it should be pointed out that noise exposure measurements are being made for different purpose and, therefore, it is important to choose the right measurements for the individual purposes. To a large extent reasonably adequate methods and instrumentation are available for exposure measurements, and in many cases they are standardized. Furthermore, if the guidelines developed in the past, although crude, would have been followed, community noise would have been a much less public health problem today. In the light of new research results, past guidelines have been proved to be generally adequate but a need for additions, refinements and clarifications has also become obvious (von Gierke, 1993).

It would be convenient if one could combine different acoustic characteristics of various noises into a single index and use this index for assessing health effects by exposure measurements. This principle has, however, been questioned both for industrial and community noises, particularly when the number of noise events is low and there are large differences between peak and background sound levels. For these reasons, the limitations of the equal-energy principle should be borne in mind for assessing adverse health effects and establishing guidelines.

With respect to noise-induced annoyance, epidemiological research data at group level are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the Leq index and often measured in dBA, but the variability has been shown to be large. Criticism has been leveled at both the mode of time integration and the use of A-weighted noise measures. It is often the maximum level which is most interesting. Moreover, information is often needed about the number of noise events and occurrence of exposures. In order to obtain a measure that correlates well with the sensitivity of hearing, today, the best thing would be to use Zwicker's calculation method for loudness, but this may still be difficult to achieve.

In the USA,, K. Stevens, Pietrasanta, et al. (1957) gave a main recommendation to use the equivalent sound pressure level in the 300-600 Hz band based on an energy average over a 1-h period. Weighted in accordance with seasonal effects, it constituted the Composite Noise Rating (CNR) measure. In 1964, in the US Air Force Manual 86-5 (Guild, Cole, Galloway, & von Gierke, 1964), a new procedure for calculating CNR was recommended which was based on the Perceived Noise Level (PNL; Kryter, 1959). The PNL was intended as a single event noise measure that linked human annoyance to the discrete frequency components contained in an individual noise event. After some improvements of the PNL measure, incorporating adjustments for the duration of flight events and for the presence of annoying tonal components, a new single noise event measure was established, the Effective Perceived Noise Level (EPNL). It was later incorporated into a new procedure which derived a new cumulative metric called the Noise Exposure Forecast (NEF) (Galloway & Bishop, 1970).

In 1974, the US Environmental Protection Agency (von Gierke, 1975) recommended that all environmental noise impact assessments should use Ldn (Day-Night Average Sound Level; also abbreviated DNL) which is based on the A-weighted energy equivalent level, penalized 10 dB for nighttime exposure, and that it be supplemented with the SEL (Sound Exposure Level; time-integration referred to 1 s, A-weighted) as a single noise event measure. As a single descriptive figure of complex noise environments over longer exposure periods, the equivalent continuous sound pressure level (Leq) was developed. Worldwide there is a trend towards a general use of a A-weighted scale sound pressure level and Leq noise measures (for an overview of measures, see von Gierke & C.S. Harris, 1987; Shepherd, 1987). However, these can be misleading by as much as a factor of three in loudness or annoyance corresponding to a difference of as much as 15 dBA (Hellman 1982, 1984; Hellman & Zwicker, 1982; Zwicker, 1985). Therefore, it seems to be necessary to develop better methods for the prediction of annoyance or loudness than A-weighted sound pressure level

(Scharf & Hellman, 1980), which may not be as simple but should be more accurate (Zwicker & Fastl, 1986).

A great effort has been directed towards finding a relationship between noise exposure metric and some measure of activity interference in social surveys (disturbance of speech communications or sleep, interference with radio or television listening, and interference with outdoor living). Different approaches have been taken to link the noise metric with the “percent highly annoyed persons” (%HA). In order to meet the demand for a uniform relationship, Schultz (1978) and later Fidell, Barber and Schultz (1991; see also Miedema, 1993; Fields, 1994) reviewed the data from a number of surveys of community reactions to transportation noises, and developed an equation for describing the relationship between the level of exposure in Ldn and the %HA. In the original synthesis by Schultz there were seven aircraft noise studies. Some later studies, though, seem to indicate that there may be some differences in the response of communities to different types of transportation noise (R.L. Hall et al., 1981; Griffiths, 1983; Bradley, 1993; Miedema, 1993). As to the predictive value of the Schultz curve, however, there is a large variation between different investigations in the Day-Night Average Sound Level that produces a certain %HA. In addition, the individual differences in response within the population are large (e.g., Job, 1988a; for variation in response criteria see B, Berglund, U. Berglund, & Lindvall, 1975b; D.M. Green & Fidell, 1991).

The types of transportation noises included in Schultz’s synthesis produce similar spectral shapes, noise levels, and temporal characteristics. It is, therefore, not surprising that they might be encompassed, at least theoretically, by the same Ldn-%HA relationships. There are, however, noise environments that are dissimilar to regular transportation noise environments or to the exposure around airports, and these could include communities exposed to sonic booms, helicopter noise, or underlying military training routes. The difference between these types of noise environments includes the number of daily flights, their occurrence in time, their onset, duration and decay times, and their intensities and spectral characteristics (von Gierke & C.S. Harris, 1987). There is currently no way to incorporate, within the Ldn-%HA relationship, flights that occur every third day, weekly, monthly, or in a general sporadic pattern.

In studying the effects of sonic booms on humans, it has been proposed that a C-weighting scale be used because most of the energy in sonic booms is contained in the frequencies below 100 Hz. It seems as if loudness calculated according to ISO 532B (1966; also ISO 532, 1975b) using computer programs and loudness measuring equipment (Zwicker, Fastl & Dallmayer, 1984; Zwicker, 1985) produce more appropriate data. This calculation is based on an approximation of the time function of the loudness perceived (Zwicker, Flottorp, & S.S. Stevens, 1957).

The attempt to relate human reactions to some noise metric/indexes is even broader than discussed above. For example, models for predicting loudness from the physical components of a sound have been developed for complex sounds. As discussed above a method for calculating the loudness in the unit sone that takes into account critical bands, mutual masking and inhibition has been developed by Zwicker (ISO 532, 1975b).

The aim of the existing noise metrics for community noise is, of course, to provide valid and accurate prediction of human effects in a novel situation, and to relate the degree of adverse effects in an exposed population to the magnitude of the noise source. The problem facing the scientific community today is the variability in the dose-response data.

In view of the fact that criteria have to be established for various land uses, traffic operating schemes, etc., the lack of a single noise metric/index that relates to a critical effect metric/index, has caused some to advocate the reduction of noise metrics/index to a single one, for example, for design of indoor spaces. Noise Criteria curves are widely used and Ldn has been suggested for air traffic noise (Shepherd, 1987). Such single noise metrics/indices would present simplicity and uniformity compared to cumulative noise measures and loudness calculation procedures. However, the loudness calculation, for example, has become drastically simplified by using computer programs (Zwicker, Fastl, & Dallmayer, 1984) instead of graphical procedures, or even more by using loudness meters with a large dynamic range (Zwicker, Deuter, & Peisl, 1985). But, loudness measurements according to Zwicker's method has the disadvantage that annoyance evoked by tonal and impulsive components are not considered (however, see B. Berglund, U. Berglund, & Lindberg, 1986). Zwicker's loudness measure was developed as an alternative to the frequently used A-weighted sound pressure level and it may be used for the same type of purposes, for example, to measure loudness-time functions for which instantaneous loudness is assessed for passing vehicles or overflying aircraft. As for sound pressure level, the loudness distributions may be calculated (Zwicker & Fastl, 1990). Zwicker's loudness was never intended to replace various noise indices such as LAeq, Ldn or NC.

Due to the fact that only instantaneous loudness was accounted for in Zwicker's calculation procedure, more recently, Zwicker (1991) introduced the concept of unbiased annoyance (UBA):

$$\text{UBA} = d\left(\frac{N_{10}}{\text{sone}}\right)^{1.3}[1 + s + f]\ \text{au} \qquad (10)$$

where d is a correction factor referable to time of day, s and f are the sharpness and fluctuations strength (both perceptual attributes of sound, for a review see Zwicker & Fastl, 1990), and N_{10} is that value of Zwicker loudness (ISO 532, 1975b) that is exceeded 10 % of the time. The UBA represents a way to predict annoyance in noise exposed populations from acoustical measurements during longer time periods. It still needs to be evaluated theoretically as well as empirically and be compared to the presently used more simple index of per cent of highly annoyed persons in subpopulations.

9.2 Issues Related to Instrumentation

In various parts of the world large amounts of money and efforts have been invested in sound level meters, in many cases of simple construction and with only weighting curve A. The developing countries have strongly emphasized that economic factors should be considered in connection with the profusion of international documents, such as noise measurement standards, and that provision be made for poorer countries to be offered the choice of inexpensive alternatives. It is politically and economically impossible to discard existing sound level meters and introduce completely new ones. In addition, it is not likely that another frequency weighting than A will be accepted unless it involves a simple adjustment of it.

At present, the IEC and the ISO are carrying out a review of the various weighting curves. The problems which are being discussed refer to tolerances rather than adequate frequency weightings, in particular in the infrasound and ultrasound ranges, as well as adequate auditory threshold values for the audible frequencies.

The description of exposure to noise with present sound level meters does not provide an unambiguous answer concerning effects without supplementary information about the noise source and/or exposure situation. Different criteria for different sources/situations are required. However, modern electronics provide almost unlimited possibilities for the treatment of signals. As a supplement to traditional sound level measurements, a conceivable procedure for the immediate future would be to register the sound event digitally for later signal processing with the required program in a suitable computer.

In order to deal with the noise problem in a relatively simple manner, the A-weighted sound pressure level measure (which gives low-frequency components less weight) has already been long in use in order to estimate the distribution of disturbances. In connection with an evaluation of noise abatement measures the A-weighted level is related to each specific source.

Conventionally, filter-weighted measurements in decibel obtained for different forms of community noise are not always in accordance with (perceived) loudness (e.g., B, Berglund, U. Berglund, & Lindvall, 1976; Berglund, Rankin, & Preis, 1990). Each filter curvature was based on an equal-loudness contour at a certain sound pressure level for a reference. The use of the particular filter is not always in accordance with the community noise of interest to measure. In the resulting measurements, the sound pressure levels above this filter-specific reference level cannot perceptually be related to the reference level for which the filter was developed.

Several problems arise when calculation of the total loudness of a composite sound is attempted. One is that noise which contains pure high level sinusoidal tones masks the sound contributions in the neighboring frequency area. In addition, there it is uncertain how to weight the influence of rapidly varying sound components (including spectral variation), impulsive sound, etc. In the latter case there is a big difference between loudness and noisiness whereas the difference is slighter when the sound is broadband. The concept of noisiness, moreover, includes a further evaluation of the sound as perceived by the individual and is, therefore, more complex than the concept of loudness. Calculation methods are available which make it possible to calculate loudness in sone on the basis of frequency spectra and sound pressure level separately.

A central question in the discussion of noise abatement measures is why some community noises are more disturbing than others. In psychoacoustic studies of how annoyance compare to loudness levels, it has been shown that one group of sounds are primarily disturbing because of the sound pattern (distinctness and identification), another group of sounds because of their sound pressure level (B. Berglund, U. Berglund, & Lindvall, 1976; B. Berglund, Rankin, & Preis, 1990). For example, aircraft noise and the sound of dripping tap water belongs to the first group whereas the sound from a typewriter or a jack hammer are typical of the latter group. The degree to which a sound is disturbing depends on individual factors, the social content of the sound and the characteristics of the surroundings (Levy-Leboyer, & Moser, 1987). For example, esthetically attractive surroundings may reduce the degree of annoyance (Kastka et al., 1986).

Better noise measurements ought to be obtainable through accumulated psychoacoustic knowledge. Psychoacoustic measurement is methodologically close to physical measurement, but with humans as the measurement apparatus. In this way it is possible to account for the different biological processes which can be disturbed by exposure to noise, for example, fatigue and stress.

In order to make full use of psychoacoustic knowledge as a basis for practical noise abatement all components of sound must be systematically analyzed with a view to their influence on the perception of sound. Important parameters in an actually occurring community noise are sound pressure levels (momentary, maximal, energy equivalent) and their distribution, frequency (spectral distribution, occurrence of pure tones), significant noise events (number, level and time distribution) and other variations (period of increase, level, spectral distribution). The problem of community noise can be described simply as a multi-dimensional problem with the physical parameters on one axis and the effects–obtained by perceptual description–such as general disturbance, sleep disturbance, speech interference and stress, on the other.

Today, we possess only incomplete information about the significant sound parameters and their relationship with the specific effects. Even less information is available on how to combine the different effects of the sound into an index which expresses the sum of the total disturbance. So far, however, it appears that an index for sleep disturbance probably should be based on maximum level and number of noise events, whereas speech interference should be based on the spectral distribution above a certain level. If the sound contains prominent low-frequency components it is suspected to be more disturbing than if the spectrum was uniform. However, with respect to noise-induced annoyance epidemiological research data on group level are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the exposure index LAeq,T, but the variability is large and predictions are therefore invalidated.

9.3 Basic Acoustics Measures

For most purposes, the following basic acoustics measures will provide a sufficiently comprehensive description of the physical characteristics of a sound at a point source. The main parameters are sound pressure, frequency, variation in time, sound character and sound quality.

9.3.1 Sound Pressure Level

The sound pressure level is a commonly used measure for the magnitude of sound. [Acoustic intensity is a special term used by engineers to describe the amount of energy transmitted in a propagating sound wave and is measured in units of W/m^2]. The sound pressure level, weighted by the A-curve, is the most common measure used in the assessment of noise exposures. Typical average sound pressure levels range from about 20 dBA in a quiet rural area at night to between 50 and 70 dBA in towns during the daytime, to 90 dBA or more in noisy factories and discotheques, to well over 120 dBA near to a jet aircraft at take-off. (Perceived) loudness is associated with the sound pressure level of a sound, but it also depends on many other factors. Some of these factors are physical, and can therefore be taken into account by a more complex physical measurement. There are also many psychological factors involved in human impressions of loudness, and these cannot be taken into account by physical measurements of the sound alone.

9.3.2 Frequency

Frequency is associated with the perception of pitch generated by a tonal sound. The frequency is measured by the number of repeated cycles of the sound wave per second; the unit of frequency is the hertz (Hz). Most sounds have more than one frequency present at the same time, and there are many sounds which cover a wide frequency range (without having any discrete single frequency component present). An example of a sound which has only a single discrete frequency present is a tone produced by a tuning fork. The first A above middle C on the musical scale has a frequency of 440 Hz. In music, this A-note is often used as a reference frequency for tuning instruments in an orchestra before performance. An example of a sound with a wide frequency range is the exhaust from a road vehicle air braking system.

The frequency is inversely related to the wavelength of the sound, such that low frequency sounds have a long wavelength and high frequency sounds have a very short wavelength. The wavelength is important when considering the propagation of a sound from a source to a receiver and when considering the most cost-effective means of engineering noise control.

The audible frequency range varies from about 20 Hz to about 20,000 Hz. An example of a low frequency source is a large idling diesel engine, which can produce large amounts of low frequency sound in the range from 20 Hz to 150 Hz. Low frequency sounds (long wavelengths) tend to travel easily over long distances. Therefore, it is most efficient to control low frequency noise at the source, although it may be difficult to obtain a satisfactory result. An example of a sound containing medium and high frequency components is a warning siren, which might typically produce a central frequency around 2,000 Hz. Medium and high frequency sounds are more easily attenuated, than low frequency sounds, by atmospheric absorption and engineering noise control.

Pitch depends on other factors in addition to frequency. The auditory system is most sensitive to the middle range of frequencies from 1,000 to 4,000 Hz. The ear is quite insensitive to very low and very high frequencies. The A-weighting used in all precision sound level meters is intended to take this differential frequency sensitivity into account. This is the reason why noise exposure is commonly measured using the A-weighted sound pressure level, expressed as dBA.

The A-weighting does not perfectly account for differential frequency sensitivity in human hearing. Certain types of high and low frequency sounds can be more annoying or potentially more harmful than a simple A-weighted measurement might indicate. An unweighted or linear measurement of sound pressure level is also useful in these circumstances. Unweighted or linear measurements should take all frequencies within the audiofrequency range into account equally. Unfortunately, while the specification for the A-weighting network has been internationally agreed, there is no similar specification for the frequency range and tolerances for a linear or unweighed sound pressure level measurement. Therefore, it is necessary to recommend the use of the C-weighting network for measurements where extreme high or low frequencies are involved, in addition to measurements using the A-weighting. This practice should be adopted until an international standard for linear or unweighed measurements may be agreed. [The C-weighting includes a much wider range of audio frequencies than the A-weighting.] The numerical difference between simultaneous measurements using both the A-weighting and the C-weighting gives an indication of the amount of the more extreme frequencies present.

A complete description of the various frequencies present in the sound requires the use of a frequency analyzer. The most common one is the FFT real time analyzer and the 1/3 octave band real time analyzer (FFT stands for Fast Fourier Transform). These can give different results depending on the type of complex sound that is being analyzed and, therefore, expert assistance is normally required. Particular caution is required for applications in which the sound pressure level changes rapidly with time.

9.3.3 Variation in Time

Sound levels usually vary with time. Rapid fluctuations in sound pressure level over less than 1 s can contribute to a subjective impression of impulsiveness, in particular where the sound pressure level rapidly increases from a low background level. Moving sources, such as overflying aircraft or individual road vehicles, produce a time-varying sound level over periods of typically 10 to 100 s. Noise from factories and other fixed installations can often be steady for much of the day, but may then drop at night.

Sound level meters are fitted with time integration circuits to regulate the speed at which the display responds to rapidly fluctuating levels. The time weighting “fast” is recommended for general use as this possibly and roughly corresponds to the loudness integration time of the human ear. All measurements of the instantaneous sound pressure level and its variation over time should use the dBA scale and the “fast” time integration unless otherwise specified. The maximum instantaneous A-weighted sound pressure level during a sound event is described by the quantity LAmax, whereby the use of the time weighting “fast” is directly implied unless otherwise stated.

The time integration “fast” has a defined time constant of 0.125 s. This means that the LAmax will not represent the true maximum sound pressure level for very short duration transient sounds lasting for less than 0.125 s. Very short duration sounds do not develop the same perceived loudness as sounds which last for the integration time of the ear or longer. Therefore, the use of the time weighting “fast” often gives a reasonable correlation with loudness under these circumstances.

A measure of the instantaneous peak amplitude is also useful, particularly in cases where the potential hearing-damage risk is threatened by high intensity, short duration sounds. If the instantaneous sound pressure variation over time can not be determined, the time integration “peak” of the sound level meter is recommended. Such measurements require a response time of the sound level meter in the order of 0.05 s. The sound level meter must then be able to store the peak value without significant decay until the reading has been recorded, and it can then be reset for the next measurement. Measurements using the peak time integration will commonly use a C- or linear-frequency weighting, and the results are often quoted directly in (root-mean-square) units of sound pressure (Pa or N/m^2) rather than using the decibel scale.

The equivalent continuous sound pressure level, the LAeq,T, is used to describe the average A-weighted sound pressure level over a defined time, T. The LAeq,T is defined as the level of a steady sound which would have the same acoustical energy at the measurement point as the fluctuating sound being measured. It is very important to report the averaging time, T. The measurement of the LAeq,T is based on the time integrations “fast” or “slow” of the sound level meter. Measurements of the LAeq,T require the use of an integrating averaging sound level meter, although there are a number of techniques available for estimating the LAeq,T where the appropriate equipment is unavailable.

The time weighting “slow”, which is still fitted to most precision sound level meters, is intended to allow the average sound pressure levels of time-varying sounds to be estimated more easily by slowing down the response of the meter display to fluctuating sound levels. The time constant of the sound level meter’s exponential averaging circuit is defined as 1 s. The continued use of the time weighting “slow” to estimate the average sound pressure level over short periods of time cannot be recommended now that true integrating precision sound level meters and analysis equipment are becoming widely available. An integrating sound level meter can provide a true average over any time period by using the LAeq,T function.

The acoustical energy contribution made by separate sound events can be represented by the Single Event Level (SEL). This unit is alternatively defined as the sound exposure level or LAE in ISO 1996/1 (1982) and as the single event exposure level or LAX in ISO 3891 (1978). SEL is defined as that constant sound level which has the same amount of energy in 1 s as the original sound event. SEL is effectively independent of the actual time over which the measurement is made. For just one event occurring during the time interval, T, the relationship between SEL (L_{AE}) and LAeq,T over this time interval, T, is

$$L_{AE} = LAeq,T + 10 \log (T/T_0), \qquad (9)$$

where T_0 is 1 s. The SEL values for a sequence of separate sound events can be used mathematically to build up the LAeq,T contribution due to that source over any defined time period. However, SEL has been shown to be inadequate for assessing the (perceived) loudness of complex impulse sounds represented by recordings of explosions from the driving charges of large-bore and small bore weapons at different distances to the source (200-4,600 m; B. Berglund, U. Berglund, & Lindvall, 1986b).

9.3.4 Sound Character or Sound Quality

The sound quality describes the particular features of a sound which identify it to the listener. Source identification can be very important in determining perceived annoyance. The relevant acoustic features can include tonal and harmonic qualities, impulsiveness, intrusiveness, roughness, the relative balance of high and low frequencies, and the steadiness or irregularity of the sound.

A major determinant of the effect of sound quality is the information content in the sound. To some extent this will vary from one listener to another. There are a range of different physical measurements which can be used to describe the different acoustic features separately, but at present, there is no general method for predicting in advance which of these will be most important to the listener in any particular case. It is generally accepted, however, that the presence of tonal content as identified physically using a frequency analyzer, or the presence of impulsive content as identified physically using an analysis of the time history of the instantaneous sound level, can usually be associated with increased annoyance. When present, other acoustic features may also be important in increased annoyance.

9.4 Usefulness and Limitations of Exposure Measures

The recommended basic acoustic measures can provide a reasonably complete description of the overall sound pressure level, but do not completely describe the frequency content, the variation with time, and the sound quality. This is because different sounds can encompass an infinite variety of different frequency contents, different patterns of variation in time and different sound qualities. In addition, no physical measurement of the sound can directly describe the attitudes, personal sensitivities and opinions of an exposed listener, or the situation and context in which the noise exposure occurs. On the other hand, the primary purpose of this document is to assist in setting standards and criteria for regulating exposure to noise in the community. It is important that such standards and criteria should be as simple and repeatable as possible, without compromising their fundamental validity. The recommended basic acoustic measures should satisfy this objective for most practical purposes.

There is a large range of more complex measures available to cover situations where the recommended basic measures are felt to be inadequate, but users of this document are requested to consider carefully whether or not the additional complication and expense involved in using any of these more complex measures is really justified in any particular case. In many cases, the purpose of providing a simple objective description of noise exposure would be better achieved by describing each facet of a complex exposure pattern separately, rather than trying to combine each separate facet in terms of some complex single number noise exposure index. The one exception to this general rule must be where the physical measurement is related to a particular complex effect, such as interference with speech communication, where the recommended basic acoustic measures do not provide sufficient detail.

9.5 Complex Measures

The main purpose of the various complex measures which have been developed over the past thirty or forty years is to attempt to provide closer correlations with observed human response than is possible by using the recommended basic acoustic measures. A traditional example is the use of the simple A-weighting for describeing the proportion of different frequencies of a sound. The A-weighted sound pressure level provides a very approximate guide to the perceived loudness of a sound, but does not in any way describe the overall character or informational content. Another example is the equivalent continuous sound level, LAeq,T which only describes the average energy content over time and can therefore conceal the pattern of variation over time which may be important in determining human adverse response. Research has shown that the recommended basic acoustic measures can be considerably improved over a wide range of different circumstances, but there appears to be little generalisability across these different circumstances. In other words, many complex measures which have been developed to suit one particular situation often fail under different circumstances, and, therefore, cannot be recommended for general use.

There is also the general problem that it is sometimes only the presence or absence of a specific noise which determines a particular human response or stress related health effect, any other physical parameter of the noise being largely irrelevant. In these cases, objective physical measurements are often of use in helping to determine the most cost-effective means of noise control.

Finally, there is the general problem that research studies are often unable to reliably differentiate between the predictive powers of different complex noise measures. This is because the relationship between noise exposure and observed effects is often quite weak, and that there are often many other factors, some unknown, which contribute to the observed effects. In addition, there will often be a high intercorrelation between candidate alternative noise measures, such that they cannot be distinguished by statistical tests. Often complex measures/indices have been developed on the basis of laboratory tests which cannot be properly validated in the field partly because field studies lack the opportunities for the precise experimental control.

9.5.1 Frequency Analysis

Sounds can vary over the auditory frequency range from about 20 Hz to about 20,000 Hz or more. Frequency analysis provides a physical description of frequency content. The main principle of frequency analysis is that any selected frequency range is divided into a number of consecutive and discrete analysis bandwidths, such that the amount of energy present in each analysis bandwidth can be determined. Different methods of frequency analysis differ in the amount of detail that can be provided and the length of time that is required to obtain meaningful results.

There are two main types of frequency analyzers in common use. The Fast Fourier Transform (FFT) analyzer takes a short sequence of digitally encoded samples of the audio signal as measured by a microphone and transforms it into the frequency domain by a complex mathematical process. The result is a narrow band frequency spectrum where the audio signal is divided across a large number of narrow analysis bands. A typical FFT analyzer divides the measured frequency range into 400 separate and linearly spaced analysis bands. In the low and mid frequency range the FFT analyzer is good for detecting narrow bands as well as tonal and harmonic components in sound, but the frequency display does not provide as good a direct correlation with human impressions as the other main type of frequency analyzer, as described below. This is because frequency resolution in human beings tends to be logarithmically spaced across the frequency range, whereas the frequency resolution of the FFT analyzer is linearly spaced across the frequency range.

The other main type of frequency analyzer, fractional octave analyzer uses logarithmically spaced bandwidths which should be located at internationally agreed octave and one-third octave spacings. The logarithmic spacing means that the bandwidth of each consecutive band increases with frequency. Frequency resolutions down to 1/24 octave are currently available in commercial instruments. The 1/3 octave band analysis is regarded to give the best approximation of the critical bands which are used in human auditory processing. Thus, a frequency analysis, using a fractional octave analyzer, usually gives a closer association with human sound perception than an FFT analysis, but it is sometimes less useful for informed decisions concerning cost-effective noise control.

One important consideration in respect of all frequency analyzers is the real-time rate. The simplest types of frequency analyzer step through the different frequency bands sequentially. More complex analyzers can display the entire frequency spectrum at once, but they do not necessarily do this continuously. A true real-time analyzer can calculate and display the frequency spectrum at the same time and continue to acquire new data, and will then update the spectrum display as required. Some analyzers cease acquiring new data when calculating the frequency spectrum and this can be a problem in the case of time-varying sounds. Transient impulsive sounds can be missed completely by analyzers which do not operate in real time up to more than the highest measurement frequency.

9.5.2 Loudness Measures

As discussed above the (perceived) loudness of any given sound increases as the sound pressure level increases, but this does not mean that different sounds with the same sound pressure level will have the same (perceived) loudness. The loudness level of any given sound can be measured in the unit phon. The value in phon of a given sound, which is found by the aid of psychophysical loudness-matching experiments, have the same perceived loudness as a defined reference sound (commonly a tone at 1,000 Hz) and is numerically equal to the sound pressure level in dB of the defined reference sound. The sound pressure levels of the two sounds could be quite different.

Over the past 30 years, a number of different complex loudness prediction procedures have been proposed which are capable of predicting the loudness of a given sound in phon with reasonable accuracy. The measurement procedure always requires either an octave or 1/3 octave band frequency analysis of the given sound. Or, in some cases, a special frequency analysis is made where the auditory spectrum is divided into a consecutive series of defined auditory critical bandwidths, expressed in the unit Bark. These critical bandwidths are broadly equal to the 1/3 octave bands over the greater part of the auditory frequency range.

Although loudness level usually show a higher correlation with (perceived) loudness (as determined by listening experiments) than simple A-weighted sound pressure level measurements, practical experience has shown that for many practical purposes, the basic acoustic measures are adequate. In addition, the accumulated data necessary for the purposes of setting criteria and standards is still lacking for the more complex loudness measures. However, care has to be taken in respect to the uncertainties and variability expected due to the use of a crude measure such as sound pressure level. Futhermore, apart from acoustical variables, many other situational and non-acoustic factors are known to contribute to the final adverse effects of noise exposures. Therefore, an increased accuracy in the measurement of some of the acoustic variables contributing to the effects on humans, does not greatly increase the overall predictive validity. This is particularly true when the loudness measure in use does not properly account for all the different acoustic features of relevance.

The most successful loudness prediction procedures to date have two main underlying principles. The first principle is that there is an underlying absolute scale of loudness involved in the process of auditory perception. This principle underlied the development of the sone scale of loudness, where a 1,000 Hz tone at a sound pressure level of 40 dB is defined as having a loudness of 1 sone. Therefore, the value of 1 sone is assigned to the loudness level of 40 phon of a 1,000 Hz tone. Each 10 dB increase or decrease in sound pressure level implies a doubling or a halving of the perceived loudness measured in sones. A 1,000-Hz pure tone at a sound pressure level of 50 dB (50 phon) has a loudness of 2 sone and a 1,000-Hz tone at a sound pressure level of 60 dB (60 phon) has a loudness of 4 sone.

The second principle is that the perceived loudness of a sound which has spectral components distributed across the auditory frequency range can be predicted from a summation of the separate loudnesses in each separate auditory filter band, as determined by fractional octave frequency analysis. The upward spread of masking where high frequency components tend to be partially masked by lower frequency components (but not the other way around) would normally be taken into account. Each separate perceived loudness prediction procedure must specify rules for taking summation and masking into account. These rules may differ, depending on the absolute sound pressure level, and are usually developed on the basis of agreed psychoacoustic data and after extensive series of listening experiments. It is also possible to take other more complex physical factors into account, if the additional complexity is felt to be justified.

In general, perceived loudness prediction procedures require an octave or 1/3 octave band frequency analysis of the sound. The individual band levels are converted into sone levels and then summed together, taking the upward spread of masking into account. The final output in sone can then be converted back into a presumed perceived equivalent in sound pressure level of the defined reference sound, expressed in phon.

A number of studies has been conduced with the aim of predicting the perceived loudness of complex sounds. These have shown that significantly improved correlations can be obtained in listening experiments when using direct numerical magnitude estimation or when using a whole range of different scaling techniques intended for quantifying perceptual variables. On the other hand, there are also a number of studies in the literature which report situations in which existing perceived loudness prediction procedures do not perform well. In addition, there is a fundamental philosophical objection to these procedures. Human perception may be geared towards constructing an image of the outside world around the observer, and not towards measuring the absolute magnitude of the physical stimulation at a peripheral sense organ. This means, for example, that perceived loudness judgments for a distant aircraft flyover might be higher than for a nearby road vehicle, even where the sound pressure level at the listener's ears due to the road vehicle is actually greater than that due to the aircraft. No simple physical measurement procedure can take this type of psychological expectation effect into account, but concerned and informed judgment is required among decision makers.

9.5.3 Time Domain Statistics

Most community noise exposures vary over time. As noted above, the recommended basic acoustic measure to deal with variation over time is the equivalent continuous sound level LAeq,T. As an average, the LAeq often conceals the pattern of variation over time which may be important in determining human response. It is important to distinguish here between very short-term fluctuations in sound pressure level occurring over periods of a second or less, medium term fluctuations occurring over periods of up to an hour, and daily and weekly fluctuations in sound level. Very short term fluctuations are associated with impulsivity, which is dealt with separately below. Medium term fluctuations are best dealt with by either showing a typical time-history of sound pressure level during a representative period of time, or by reporting a range of time domain statistics to show the extent and frequency of the fluctuations. Daily and weekly fluctuations are best described by reporting average levels separately for each separately definable period. For example, community noise exposure often varies significantly between day, evening and night-time periods. For obvious reasons, community sensitivity often varies considerably at these different times. Therefore, it is often desirable to set different criteria for acceptable noise exposure for each of these different time periods. Daily average sound exposure measures with different weighting factors for noise exposure at different times of the day and night such as the Ldn as used in the USA, are an effective but crude way, taking daily variations in human sensitivity into account.

All time domain statistics as used for describing medium-term fluctuations are based on a sequence of samples of the instantaneous sound pressure level. It is important to be specific as to the particular time weighting or sound level meter averaging process used in deriving the sample sequence. For most purposes the running instantaneous sound pressure level should be determined using the “fast” time integration and be sampled at 1 s intervals or less. It is preferable to derive a sequence of consecutive 0.125 s linear averages where the appropriate equipment is available. A number of time domain statistics can then be used to describe the sample sequence as measured. Percentage of levels in excess such as the L_{10} (the level exceeded for 10 % of the time) are used in some national standards to describe the average maximum levels of separate events within the time history sequence, and the L_{90} (the level exceeded for 90 % of the time) to describe the mean minimum steady background noise level. The L_{01} (the level exceeded for 1 % of the time) gives an indication of the maximum instantaneous sound level (Lmax) recorded during the sample sequence, but it will usually be slightly lower than the true Lmax during the sample sequence. The standard deviation of the mean of the sample sequence gives an indication of the range of fluctuations in level from the maximum to the minimum. Other statistical descriptors can be used for special purposes.

9.5.4 Acoustic Features

There are a number of acoustic features such as relative frequency content, tonality, impulsivity, and regularity which determine the sound quality and might convey additional informational content to the listener. These features often specifically identify the sound to the listener and allow it to be distinguished from the residual background noise. There are cases where it is the specific feature itself which is the direct cause for complaint, and not the sound level per se. In general, there is no agreed measurement procedure to determine the presence or absence of such features, which must be left instead to the discretion of the investigating officer or other nominated officials, who has delegated regulatory powers. This situation is unsatisfactory and there is research in progress in a number of institutions around the world to attempt to rectify this deficiency.

9.5.4.1 Relative frequency content

All other things being equal, sounds which are predominately high-frequency in nature tend to be more annoying than sounds which are predominantely low frequency in nature. In turn, noises with a high proportion of low frequency components are perceived as more annoying than other noises of equal sound pressure. The sounds with dominating high-frequencies may be assessed by sharpness measurements. However, such measurement methods have not yet been agreed upon for practical environmental use, although sharpness values are being considered in the noise control of various products (e.g., components in cars).

9.5.4.2 Tonality

Recent research has confirmed that the subjective tonality and tone sensation level above threshold of discrete narrow band components in a broadband background noise can be reliably predicted from a narrow band frequency analysis of the tone plus noise combination. The auditory threshold of a tone in broadband background noise (and hence the sensation level) can be estimated from the relative levels of the tonal component and the surrounding auditory filter bandwidth of the broadband background noise. It is necessary to be particularly careful in the selection of the most appropriate frequency analysis filter bandwidths for this type of evaluation. Further research will be required to develop more complex procedures for the objective determination of the auditory threshold and hence the sensation level of harmonic and inharmonic tone complexes in broadband background noise, or to take the relative audibility of one tone complex as heard against another different tone complex into account.

9.5.4.3 Impulsivity

Perceived impulsivity is dubious to predict from physical measurements. In general, any sound pressure level time history showing rapidly rising event onset times is likely to be judged as containing impulsive components. There are a range of different physical measurement procedures which take event onset times into account in different ways, but there is no method which is universally applicable. A number of statistical measures obtained from a sequence of very short time (5 or 10 ms) consecutive linear averages derived from the instantaneous sound pressure level time history have shown promise in the laboratory, but the relative frequency content can also be important. Perceived impulsivity can contribute to annoyance, but there are also sounds which are judged to be both impulsive and not annoying.

9.5.4.4 Regularity

Medium-term variations in instantaneous sound pressure level can be thought of as another feature which can draw attention to a noise. A well known example of this is the low level, low frequency, rhythmic sounds which might emanate from a poorly insulated discotheque. Such sounds can often be readily identified by an average listener even when it is difficult to obtain a direct measurement because the acoustic instruments used do not have the same sensitivity as human hearing. So far, there is no agreed or standardized physical measurement procedure available which can be used in such applications.

9.5.4.5 Informational content

There are many other possible acoustics features which are best considered as adding informational content to the sound, in the sense that they might have speech like qualities or possess some particular properties of interest to certain listeners. Recent research has confirmed that informational content is one potent factor in noise annoyance, apart from loudness and intrusiveness of sound (B. Berglund, Harder, & Preis, 1994; Preis & B. Berglund, 1994). However again, there are no agreed general procedures for dealing with such sounds, although there are specific measures such as STI measurements (see below) which may be used in particular cases.

9.6 Examples of Specialist Measures

There are a number of complex measurement procedures which are used in specific areas of noise assessment and control, but which nevertheless fall outside the scope of the recommended basic acoustic measures. These measures have been discussed above but are described in more detail below.

9.6.1 Perceived Noise Level

The international aeronautical industry has adopted a particular complex noise measurement procedure for describing aircraft noise heard on the ground. The defined procedures are set out in ISO 3891 (1978). The agreed procedures include calculations to give an approximation to the perceived noise level (PNL) as determined by listening experiments on a fundamental psychoacoustical basis. The perceptually determined PNL of a sound is defined as being numerically equal to the sound pressure level of a reference sound (defined as a frequency band limited random noise signal from 910 to 1,090 Hz) that is judged by listeners to have the same perceived noisiness as the given sound. The underlying philosophy of the PNL prediction procedure makes a clear distinction between loudness, noisiness, and annoyance, as separately distinguishable perceptual attributes of a sound. Loudness is thought of as being a neutral property of a sound, whereas annoyance depends on many other factors in addition to the sound pressure level per se. Noisiness is in between, in that it is intended to describe the inherent undesirability of a given sound, but without being influenced by the context in which the sound is heard. The PNL calculation procedure is broadly similar to a number of complex perceived loudness prediction procedures as described above.

In essence, the method for calculating PNL requires a 1/3 octave band frequency analysis of a time varying aircraft flyover sound to be carried out at least every 0.5 s over the frequency range from 50 to 10,000 Hz. Each 1/3 octave band level is then converted to an equivalent “noy” value using a frequency dependent formula which is given in the ISO standard, using an analogous method to the way in which band levels are converted to separate loudnesses in sone in standard loudness prediction procedures. The separate 1/3 octave band noy values are then summed using a formula which takes the arithmetic sum of each band noy value and the maximum band noy value into account (cf. S.S. Stevens formula for calculating loudness, ISO 532A, 1975b; see also ISO R532, 1966). The total noisiness value in noy is then converted back to an equivalent PNL quantity expressed in decibels by using a further formula.

Additional corrections are specified to take spectrum irregularities, such as those due to pure tones and the duration of the aircraft flyover into account, to give tone-corrected PNL and effective perceived noise level (EPNL), respectively. The tone correction procedure is not robust against the detection of spurious tonal content due to the interaction of the direct and ground-reflected waves at the measuring microphone, or even due to the removal of any particular band level from the analysis because of possible contamination by background noise. It should therefore be used with caution. The duration correction is effectively an energy integration of all the separate tone corrected PNL as determined from consecutive spectra taken at 0.5 s intervals and referenced back to a standardized duration allowance of 10 s.

9.6.2 Acoustic Intensity Measurements

Acoustic intensity is a specialist measure used by engineers to describe the physical power per unit area in a propagating sound wave, expressed in units of watts per square meter (W/m^2). Conventional sound pressure level measurements are independent of the direction of the sound wave as pressure is a directionless quantity. This is usually of no consequence when assessing the effects of sound in humans, but it is sometimes important when designing cost-effective engineering noise control. Most physical objects vibrate in a complex pattern when radiating sound, such that different parts of the surface contribute different amounts of energy to the sound field radiated into the far field from the source. Sound intensity measurements are capable of describing the flow of acoustic energy away from the source, and picking up which parts of the surface are making the greatest contribution to the radiated sound field. This information can then be used by an engineer to target noise control measures more effectively. For example, there is little point in damping the vibrations of a part of the source which is not making a large contribution to the radiated sound field when other parts of the surface are making a greater contribution. Sound intensity can be expressed as a sound intensity level by converting the units of Watt per square metre to a decibel quantity.

Sound intensity measurements can also be used to determine the total radiated sound power of a source. This quantity can be expressed in Watt, or converted to a sound power level expressed as a decibel quantity. The total sound power radiated by the source can be found by integrating the sound intensity radiated in each direction around the source over the total area of an imaginary surface around the source on which the intensity measurements have been taken. The sound power of a source is useful when making predictions of the effect of adding a new sound source into a reverberant space, such as when adding new noisy machines into an existing factory, but it provides no information regarding the direction of the sound radiated by the source.

Sound intensity measurements generally require the use of a special probe comprising at least two precision matched microphones. The sound intensity vector along the line joining the centers of the two microphones can then be calculated from the relative amplitudes and phases of the acoustic pressures as detected at each microphone. All such calculations are normally performed by the measuring instrument which will then display the intensity directly.

9.6.3 Speech Transmission Index

The speech transmission index (STI) is a specialist measure used by engineers to predict the effectiveness of speech communications in conference rooms, auditoria and by electroacoustic systems. It is particularly important to be able to set a minimum standard for speech intelligibility for audio public-address systems which are intended to assist in the emergency evacuation of any area which are accessible to the public, such as transport facilities, sports grounds and leisure centers, shopping malls, office buildings, industrial sites, etc.

Speech intelligibility is defined as the proportion of spoken messages which are correctly understood. In theory, it should only be measured by a behavioral test, where spoken messages are broadcast through the system being tested and, for example, the numbers of messages correctly understood are counted. It is normally assumed that the messages are broadcasted, using the native language of the talkers and listeners unless otherwise stated and that there are no significant speech impediments or hearing defects. Intelligibility as measured in this way is highly dependent on the type of messages being broadcast, the particular properties of the talker’s voice, and on the motivation and degree of practice of the listeners. For example,where there are only two alternative messages which are chosen for the maximum acoustic contrast, intelligibility is likely to be very high, even when the acoustic conditions are poor. On the other hand, it is unusual to record 100

% intelligibility even under ideal acoustic conditions when there is an infinite choice of messages. This is because most listeners will usually make a small percentage of mistakes when listening to unfamiliar material. It is better to deal with residual errors by incorporating repetition and other forms of redundancy in important messages than by attempting to develop better than perfect public -address systems.

Physical measurements, that have been shown to give a reasonable correlation with behaviorally determined intelligibility, are preferred for the purpose of demonstrating compliance with standards, and avoid the considerable complication of carrying out properly controlled behavioral tests. In addition, the use of physical measurements in performance standards will usually allow for detailed engineering design to proceed against clear physical criteria, which is much to be preferred to the alternative situation of design by experiment. The STI is the most widely validated objective measurement procedure which is capable of giving reasonable correlations against behaviorally determined intelligibility, and therefore, can be recommended for use in setting performance standards for most purposes.

In essence, the STI requires the calculation of a weighted sum of modulation indices determined over a wide range of representative speech frequencies. The talker is simulated by a transmitter device which generates cosine amplitude modulated 1/2 octave bands of noise over modulation frequencies and 1/2 octave band center frequencies which are representative of normal speech. A receiver device then determines the extent to which each of the separate modulation frequencies can be recovered against the effects of background noise and reverberation and the effects of non-linear distortion which can typically occur in electroacoustic systems. The weighted sum of the separate modulation indices is scaled over the range from 0 to 1, where 0 represents no intelligibility and 1 represents perfect intelligibility.

An internationally agreed shortened STI measurement procedure is known as RASTI (Rapid STI), in which a much smaller range of modulation frequencies is tested over only two 1/2 octave noise bands. RASTI gives effectively the same results as the full STI under normal circumstances, but is less accurate when a complex system is being tested. There are also methods of deriving an equivalent STI from different types of electroacoustic measurement than that described above. These alternative methods will usually give similar results, but the effects of possible electroacoustic non-linearity may be accounted for differently.

A minimum STI value of 0.5 would normally be just about acceptable for an emergency public address system, where some degradation of the spoken messages can be accommodated by carefully selecting the talkers and the messages and by the use of repetition. There is a direct relationship between STI and the speech signal level to the background noise level ratio, and the effects of reverberation can also be taken into account mathematically. This allows STI values to be predicted from engineering data under a wide range of practical circumstances.

Real human speech is considerably more complex than the simple cosine modulated bands of noise model as used in a standard STI assessment. The STI test signal is generally representative of the frequency ranges and modulation frequencies present in real speech but it does not properly represent the periodic signals which are contained in voiced speech sounds. The signal waveforms of voiced speech sounds are periodic at the resonating frequency of the glottal source (the vocal cords) and are rich in harmonic content due to the repetitive impulsive nature of the source. The different vowel sounds are produced by different articulations of the vocal tract to generate a range of different formant resonances which are superimposed over the harmonic structure produced by the glottal source. It is only the lower level and predominantely higher frequency consonant sounds which do not exhibit periodic signal waveforms. This means that the STI test signal will not properly represent the effects on real speech signals of all possible types of signal distortion that might occur in practical systems. On the other hand, the standard STI test is adequate for general purposes provided that the more obscure types of distortion are controlled by other sections of the system specification.

9.6.4 Sound Reduction Measures in Buildings

The effectiveness of building structures for noise control are assessed in a number of ways. In general, any part of a building which is interposed between a noise source and a sensitive receiver will reduce the amount of sound energy that would otherwise be transmitted from the source to the receiver. It is often important to be able to specify the amount of sound reduction that can normally be expected from different types of construction for design purposes, or to carry out measurements after construction to confirm that design targets have been achieved. Whereas different building elements can be tested in the laboratory to select for the best sound reduction performance, the full potential is often not realized in actual construction because of poor workmanship or incorrect installation. In addition, there will often be a flanking transmission path whereby noise can still reach the receiver via another route. There is no point in specifying a partition with a high sound reduction rating between two rooms if there is a flanking path via, for example, a common ventilation system duct, with a low sound reduction rating.

The sound reduction index is defined as ten times the logarithm of the ratio of the sound power incident on the source side of the building element (or partition) to the sound power transmitted through the building element. This ratio of sound powers is estimated by measuring the average sound pressure levels in the source and receiver rooms on either side of the building element and then correcting the difference in average sound pressure levels to take the acoustics of the receiver room into account. This means that the area of the building element and the amount of acoustic absorption in the receiver room must be taken into account. The source sound field is normally generated with loudspeakers, although the real noise source which the building element is designed to protect against can also be used. The measurements are normally carried out separately in each 1/3 octave band from about 100 Hz up to about 3,000 or 4,000 Hz, or for special purposes, over an even wider frequency range, as the sound reduction index generally varies considerably at different frequencies. There are a number of schemes for combining the separate 1/3 octave band measurements into an overall single number sound reduction rating (for example, the STC rating as used in the USA and the Rw rating as used in Europe). These single number ratings are useful for preliminary design purposes, but detailed design should always proceed on the basis of a complete set of data across a frequency range that is as wide as possible.

Laboratory measurements use highly reverberant rooms on either side of the building element, which must be built into the common wall between the source and receiver rooms in such a way as to avoid flanking transmission. The source and receiver rooms should be structurally isolated to obtain valid measurements of building elements with a high sound reduction index. The use of reverberant rooms ensures that the sound fields on either side of the building element are properly diffuse. The sound reduction index depends on the angle of incidence and diffuse fields provide a good average over all possible angles of incidence.

Field measurements generally involve some form of compromise, with the intention of getting as close as possible to the laboratory situation within the constraints of the measurement site. Flanking transmission will often be a problem in terms of showing that the design target performance of a particular building element has been met when installed, but this is also a general design problem as attention will then have to be applied to the flanking path to obtain the desired degree of isolation in situ.

There are two other types of measurements which are important for building noise control. Acoustic absorption is important in cutting down reverberation, but it does not affect the strength of sound waves which are traveling directly from the source before they have been reinforced by reflections from the walls and by reverberation. An absorption coefficient of 1 means that none of the incident sound energy is reflected back into the source room. The energy of the incident sound could have been dissipated as heat in the absorbent material, or it could have been transmitted through, such as in the case of an open window. An absorption coefficient of zero means that all of the incident sound energy is reflected back into the source room. Dense solid materials such as steel plating have very low absorption coefficients.

Acoustic absorption is different from the sound reduction index. The absorption coefficient refers to the amount of sound energy not reflected back into the source room, whereas the sound reduction index refers to the amount of sound energy transmitted through the building element. An ideal building element for noise control purposes would absorb all the incident sound energy without transmitting any energy through it.

The final type of specialized measurement as used in buildings is that of impact sound reduction. Direct impacts with a building element such as a solid cast concrete floor slab can cause vibrations to be transmitted through the solid material which are then radiated as sound on the underside. Measurements require the use of a standardized tapping machine to act as a controlled impact source.

9.7 Summary

To a large extent reasonably adequate methods and instrumentation are available for exposure measurements, and in many cases, the procedures are standardized. In the light of new research results, past guidelines have been proved to be generally adequate but also that the need for additions, refinements and clarifications has become obvious. With respect to noise-induced annoyance epidemiological research data at group level are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the index LAeq,T .The variability is known, however, to be large and is seldom considered in planning decisions. Criticism has been leveled at both the mode of time integration and the use of A-weighted noise measures.

The content of the noise that affects perception is not fully disclosed by present-day noise measurements. This applies to the effect of pure tones, dynamic characteristics (period of increase, pressure variations, impulsive sound) and signals that are close to each other in frequency but somewhat staggered. In practice, frequent measurements are being made but often about aspects which are less essential for human health and comfort evaluations.

In the present noise measurement systems, certain improvements can be introduced. For example, Zwicker's method for calculating loudness can perhaps be used better and his method for predicting unbiased annoyance (UBA) should be explored for fluctuating environmental sounds. Every equivalent continuous sound pressure level measure can, if properly used, be suitable as a prognostic instrument for assessing the noise situation but not the adverse effects that may result thereof.

The following components of noise should be considered in the evaluation of countermeasures against noise exposure: time factor (sound and effect as a function of time), level (equivalent, momentary, background, individual sound events with regard to peak value, repetition frequency of impulses), tonal character (spectra and combination of spectra), low-frequency content, rise and fall time, and information value. As the basis for a simplified analysis (e.g., Botsford, 1969), it is suggested to use: sound pressure level in dBC and dBA and their difference as a first estimate of the low frequency content as well as number of exposure events, and occurrence of exposures during a 24-h period/week.

In selecting the best method of measurement, the aim of the measurement has to be clarified. There are three main objectives: (a) The measures should correlate with the specific adverse effect, for example, speech intelligibility, loudness, annoyance, hearing loss, sleep disturbance, etc. In this respect the speech intelligibility and loudness should be measured by STI (or AI) and Zwicker loudness, respectively. (b) Within exposed environments, like homes or workplaces, adverse noise effects should be reduced including several effects: annoyance, speech intelligibility, performance, etc. Therefore, one of the measurement methods may be chosen, such that it corresponds to the most prominent of the effects. (c) In prospective noise control, the anticipated exposure has to be predicted from parameters of various sound emissions from sources as well as sound propagation models from emission to immission (Kurze & Beranek, 1971; Hallberg, C. Larsson, & Israelsson, 1988). In this case, the concern for specific effects and specific environments have to be considered jointly and appropriate effect-related measures forecasted.

10 EVALUATION OF HEALTH RISKS FROM EXPOSURE TO NOISE

10.1 Principles of Assessing Effects

In assessing noise-induced effects the global criterion is "human health". The established definition by the World Health Organization says that health is "a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" (WHO, 1947). This is a wide conceptualization which explicitly covers impacts such as disturbance and impairment of human activities and related annoyance reactions. With respect to physiological as well as psychological effects of noise exposure, most research and recommendations over the last decade emphasize the importance of the total noise exposure of people (occupational, community, and leisure time noise). If one for administrative purposes separates the criteria for these, it is emphasized that with respect to "health" these exposures must be combined. For a vast majority of the population, the concept "community noise" is analogous to occupational exposure, particularly in industrialized countries.

For assessing noise effects, relevant aspects of human behavior have to be identified, such as work, communication and social interaction, residential activities, recreation and sleep. For each of these areas, adverse physiological, psychological, sociological and economic consequences of exposure to noise need to be critically evaluated.

Evidently, the required evaluation is a difficult and demanding task. In assessing the severeness of noise effects, some meta-criteria are helpful.

Critical questions are whether noise impacts occur at nearly all times (i.e., every day, at all day or night times, etc.) or during restricted times only, whether effects are irreversible or not, whether enduring impairments of physical or mental health are observed, whether exposed people can avoid or reduce their exposure, and whether some sort of compensation of noise impacts is possible.

Almost all noise effects are undesirable, yet in many cases it is not definite whether these effects must be judged as harmful and thus as unacceptable or not. Ultimately this is a normative and societal decision.

10.2 Defining Critical Limits

Environmental "standards" define exposure limits beyond which the impacts of a stressor are "critical" i.e., "dangerous", "harmful", "intolerable", "unacceptable" (DeKoning, 1987; Salter, 1988). Although the target criteria are effects (aspects of health and wellbeing which are to be protected), critical limits are commonly expressed in terms of the stressor which causes the risk for exposed people, that is, the noise load.

As with most environmental factors, different types of standards/limits are to be distinguished (Rohrmann, 1990a):

(a) emission versus immission standards,
(b) peak versus average emission/immissions,
(c) restrictions for the level or the time of the noise, and
(d) definite limits (law-enforced) versus target values.

Most noise standards are specific for sources (road traffic, aircrafts, machinery, factories, etc.) and environments (homes, workplaces, etc.), and they usually consider several additional exposure factors (e.g., time of day, tone/impulse components, type of area in which the noise occurs, etc.). This leads to a large diversity of acoustical noise descriptors (see Finke, 1980; Tempest, 1985).

In order to define and substantiate noise standards, scientific investigations are necessary. However, the actual "critical limits" cannot be found by research. Standards are set by society as the outcome of a normative effort, rather than emerging from an objective "scientific" result (Irle, 1975; Jansen, 1986; Kutscheidt, 1989; Rohrmann, 1993). Five questions need to be clarified when setting noise standards (Rohrmann, 1990a): Which effects occur; are these caused (or at least affected) by the noise immission; which kinds or degrees of effects are unacceptable; above what exposure levels are they likely or certain to occur; which type of standard would be most protective?

From a pragmatic viewpoint, efficient standards need to be strict, unambiguous, transparent, practically feasible, and controllable. The typical approach to noise control by ISO-standards is based on: (1) the sound emission of sources being described by sound pressure level (A-weighted or in octave-bands), and (2) the sound exposure as described by energy equivalent continuous sound pressure level, LAeqT, measured or predicted, and to which may be added adjustments for time history, spectrum, maximum-level, etc.

The various ISO standards in the noise field mark significant steps forward and have received much scientific scrutiny and extensive discussion and, thus, represent the result of years of hard work and compromise. However, even well-founded noise standards will always be imperfect, even for exposure assessment. Furthermore, acoustical criteria cannot distinguish precisely, but in approximation only, between people with high or low disturbance/annoyance/impairments. The reason is that the relation between ”dose” and ”effect” is not very strong because of large individual differences (correlation coefficients are at best about 0.5). A careful consideration of context factors can reduce this problem.

As noise protection standards are very consequential, the standard-setting institution/committee must be carefully selected, balancing societal, administrative and scientific aspects (DiMento, 1981), and act according to well-defined and transparent principles. The efficiency of the employed measures should be investigated by evaluation research.

Finally, if past guidelines would have been followed, or could be followed, people would hardly have a problem with most community noises. In the light of new research results, past guidelines have proved to be useful in many practical contexts. But some additions, refinements, and clarifications are needed. This document intends to provide that information.

10.3 Indices of Population Response

Community reactions to a noise source can be expressed in many scales: mean degree of annoyance, percent highly annoyed, speech and sleep interference, complaints, activity disturbance, and others. In social surveys on annoyance, the main emphasis has been on elucidating the effects on exposed populations with respect to the ambient noise load. When analyzing response data over the past decades, the large variability is striking. There are so many sources of variability in an individual’s exposure situation and reaction to noise that it is impossible to obtain useful mathematical relationships between noise and response without controlling for individual differences in exposure and response.

Noise measures are, in general, reproducible and fairly consistent for various types of instrumentation. The different noise measures usually correlate fairly well among themselves. In spite of much research no new metric or descriptor of cumulative noise exposure, to replace Leq and Ldn, has emerged and they have become international standard (ISO 1996, 1982, 1987b, 1987c). To improve on this basic standard, adjustment factors have been proposed for impulsive noise, tonal components, noise information, special noises, etc. Supplemental measures have been proposed for evaluating single events (Sound Exposure Level, SEL), for example, of aircraft noise and sleep interference. Thus exposure measurements are being made for different purposes and the important point is to make the right measurements for the individual purpose. One real shortcoming is the lack of individual around-the-clock monitoring and dosimeters for this purpose are not available.

A main problem seems to lie in the procedures by which response data are obtained. The traditional methods for measuring population annoyance (e.g., % highly annoyed) implicitly postulate that response criteria are invariant. However, in studying response criteria in differently exposed populations to aircraft noise, it has been shown that response criteria are dependent on the exposure conditions (B. Berglund, U. Berglund, & Lindvall, 1975b, 1975c; B. Berglund, U. Berglund, E. Jonsson, & Lindvall, 1977; see also D.M. Green & Fidell, 1991).

Scales of annoyance from different populations will show systematic differences in the units of measurement as a function of exposure condition. More variance is introduced when going from one exposure condition or one region or country to another (Namba, Kuwano, & Fastl, 1987). A criterion level set in terms of a physical noise pollution index implicitly assumes that the underlying dose-response relationship is unequivocally determinable. Therefore, a simple correlation between dose and response is insufficient abecause the mathematical form of the relationship has to be known.

The physical noise pollution index and the perceived environmental quality index must be derived from psychological scales that are possible to calibrate. Of course, it is possible to work with uncalibrated scales when comparing responses to a particular set of items at a particular time within a particular group of observers. However, as soon as comparisons are to be made between different groups of observers, for example, belonging to different residential areas or work places, calibrated psychological scales are necessary. The calibration must be conducted with regard to some known conditions, preferably independent of the environmental condition under study. Thus, the aim is to equalize the frames of reference for the observer groups involved (B. Berglund, U. Berglund, & Lindvall, 1987; B. Berglund, 1991).

Various approaches to calibrate loudness or annoyance response scales have been tried by Galanter, Golding and Harber (1977), B. Berglund, U. Berglund and Lindberg (1983), B. Berglund, U. Berglund and Lindvall (1987), and Galanter (1991). B. Berglund and associates (e.g., B. Berglund, 1991) developed a Master Scaling procedure, in which individual differences in response behavior can be controlled. Such a scale provides a defined unit of measurement of the attribute and the procedure will retain the information about the observers' individual differences in scaling performance. The perceptual attribute is expressed either in calibrated perceptual units or in equivalent physical units, both in terms of the Master Scale. The calibration method developed by Galanter (1991) utilizes a Utility Comparison Scale in annoyance surveys which calibrates annoyance to a numerical disutility that can be equated to a monetary loss.

In practice, few if any, dose-response curves are based on calibrated response scales, in spite of the fact that the points along the curves are often derived from both different observer groups and different environments. In addition, often both the physical noise pollution indices (e.g., cumulative noise metrics) and some response scales, are ordinal scales (rank-order information) that cannot be calibrated (B. Berglund, 1977).

As to the construction of a dose-response model, the physical noise pollution index is often the empirical result of one large investigation. Few indices have stood the cross-validation test. Instead they seem to survive because they are claimed to have practical validity. However, a scientific cross-validation in the form of a new empirical investigation is virtually indispensable when the physical noise pollution indices are based on human responses.

Criteria such as percent "highly annoyed" (%HA) have inherent methodological problems:

(a) The selection of the subs

manipulated and also affect the form of dose-effect functions (see Rohrmann, 1984).

(b) Response criteria, particu

(c) Average-based indices ig

To reduce the large variability obtained in annoyance surveys which restrict their usefulness, the survey response scales should be developed and improved to increase comparability. In waiting for this research a pragmatic, less sophisticated but also less reliable approach have to be taken. In order to gain statistical figures about the extent of disturbed or annoyed people, systematic social surveys with representative samples, employing a standardized questionnaire, may be conducted. Alternatively, estimations might be possible. In that case two sets of data must be available: the number of people exposed to relevant noise levels, and the dose-response relationship for the particular type of noise and type of population. From this information an estimation may be made of the proportion of those exposed who feel themselves disturbed or annoyed by the noise.

Indices of population responses to community noise exposures are much needed, for example, for evaluating the severeness of a noise problem, or for allocating limited resources to the cost-effective noise abatement activities.

10.4 Consideration of Vulnerable Groups

The evaluation of noise effects and related protective standards are virtually based on data from "normal", "average" people. They are usually adult participants of investigations, selected as representative samples of the general population, or sometimes because of availability. However, people having less abilities and/or possibilities to cope with the impacts of noise exposure, and thus being at greater risk for harmful effects, might be underrepresented or insufficiently considered in noise protection necessities.

Examples of vulnerable groups are: people with particular diseases or medical problems (e.g., high blood pressure), people in hospitals or in rehabilitation, people dealing with complex cognitive tasks, the blind, people with hearing impairment, babies and young children and elderly in general (see also Jansen, 1987).

For every noise protection guideline the issue of vulnerable subgroups of the population has to be considered. This is valid for types of effects (communication, recreation, etc.) as well as for places of exposure (home, workplace, public institutions, etc.).

10.5 Health Risks to Occupational Noise

10.5.1 Populations Affected

Intense noise is a feature of several work environments and extensive efforts are necessary to reduce the incidence of occupational hearing impairment. Noise-induced hearing loss occupies a leading place among occupational diseases, and, in all nations, industrial noise abatement and hearing protection programs should be a matter of priority for bodies that are responsible for the health of the working population.

People who work in less noisy places may run less risk of occupational hearing impairment and accidents but could suffer from other noise-induced ailments derived from stress or chronic fatigue. Noise causes difficulties in communication and in work conditions in a wide variety of occupations.

10.5.2 Physical Injury

Exposure to sound pressure levels exceeding 130-140 dB, even for short periods, involves a risk of tissue damage to the ear (e.g., rupture of the tympanic membrane).

Aural discomfort is experienced at sound pressure levels above 100-110 dB, among sensitive people even at lower levels, and acute pain begins at sound pressure levels above approximately 130 dB. This must be considered as a warning signal of incipient damage and an urgent requirement for preventive or protective measures. Painful sound intensities are far above those that cause hearing loss, when regularly experienced for several hours per day, and even brief exposure to such levels should be avoided.

10.5.3 Hearing Impairment

Long-term exposure to intense noise can result in a gradual impairment of hearing. The time scale of this process varies considerably depending on individual susceptibility, noise intensity, spectrum, and exposure pattern, and many other factors not yet fully understood. In some people, severe damage may be caused in the first few months of occupational exposure; in others, hearing loss can develop gradually over the whole period of a working life. Combined with presbyacusis (hearing impairment by aging), it can lead to severe handicap and disability that is not amenable to treatment.

There is considerable variation in human sensitivity with respect to hearing impairment. In spite of much research, no method has yet been found to identify individuals who may be particularly susceptible to noise-induced hearing loss. For this reason, it is extremely important to avoid exposure of workers, and others, to noise levels that are known to involve a risk of permanent hearing loss. This should be achieved by effective noise-control measures. If this is not possible, then workers should

be protected by a hearing conservation program following recognized occupational health standards.

Early detection of incipient hearing impairment is most important in the prevention of progressive deafness. Since the earliest loss of auditory acuity usually occurs at frequencies in the region of 4,000 Hz, loss at this frequency is the most sensitive indicator of incipient damage. Losses at lower frequencies usually indicate progressive damage. Noise-induced temporary threshold shift is occasionally used to predict permanent threshold shift, but there is little agreement on the validity of this practice.

There is some disagreement concerning the relationship between the relative hearing-damaging capacity of the sound pressure level and its duration. Therefore, to assess the noise-induced loss of hearing capacity the influence of sound pressure level and duration are taken into account separately. The hypothesis that the hearing damage associated with a particular noise exposure is related to the total energy of the sound (i.e., the product of intensity and time) is used for practical purposes to calculate the noise load over a short time interval such as one or, exceptionally, some days. Thus, from a hearing impairment point of view, noise is primarily described in terms of equivalent continuous sound pressure level, Leq, measured in dBA. For occupational noise, the level is usually averaged over the entire 8-h shift (Leq,8h), and, exceptionally, over 40 h per week.

The hazardous nature of a noisy environment is commonly described in terms of “damage risk”. This may be expressed as the percentage of people exposed to that environment who are expected to suffer noise-induced hearing impairment after appropriate allowance has been made for hearing impairments due to other causes, mainly aging. Analysis of the available data has provided a statistical basis for predicting the degree of hearing loss likely to be experienced by people exposed to steady-state noise during an 8-h working day, for periods up to 40 years. The risk is by most scientists deemed negligible for ≤75 dB LAeq,8h, but some might say below 80 dB.

Above the former limit, the risk of noise-induced permanent hearing impairment increases with increase in noise level, although the risk increment may be difficult to demonstrate in the individual case but only in group data. However, the threshold value below which noise can damage hearing may be even lower than 75 dB LAeq,8h, in cases when the noise exposure is combined with ototoxic drugs, chemicals, vibration, or shiftwork.

If the significant noise exposures are concentrated over shorter periods during the day, the basic criterion of 75 dB LAeq, 8-h, implies that the risk would also be negligible with a 4-h exposure to 78 dBA, a 2-h exposure to 81 dBA, and a 1-h exposure to 84 dBA. Conversely, if additional exposure occurs outside the eight working hours, for example as a result of commuting to work or leisure activities, the limit of safe exposure, in spite of the lack of conclusive evidence, may be estimated as 70 dB LAeq averaged over a 24-h day.

Any comparison of noise exposures with recommended exposure limits should be based on measurements taken at the worker’s ear under actual working conditions. Sound pressure levels should be monitored at periodic intervals. For fluctuating exposures, the LAeq for the total workday should be determined. If the noise contains impulsive components, the peak pressure, duration, and repetition rate of the impulses must be compared with separate limits, in addition to those just stated or impulse adjustments be added to the LAeq.

Hearing disability may be assessed in terms of difficulty in understanding acoustical signals and speech. The amount of loss at the speech frequencies has been used as a basis for monetary compensation and varies from one country to another. The unweighted average of the losses, in dB, at 500, 1,000 and 2,000 Hz that is widely used for assessing noise-induced hearing impairment, is misleading. Noise-induced hearing deficits usually occur at 2,000 Hz and above, and the main speech frequencies are 500 to 4,000 Hz. Therefore, frequencies of 3,000, 4,000 and 6,000 Hz are also included in some damage assessment formulae (ISO 1999, 1990), and the common approach to assess hearing loss is to include 500, 1,000, 2,000 and 4,000 Hz, or 1,000, 2,000 and 4,000 Hz, or 3,000 Hz, alternatively.

Based on available risk tables, legislative provisions or recommended practices adopted by several countries specify occupational exposure limits in the range of 85±5 dB LAeq,8h with an increasing tendency to aim at lower limits. The level 75 dB LAeq,8h, can probably be considered as the limit below which there is little or no risk of permanent hearing damage and no necessity for protective measures, provided there is no other exposure with which noise may interact that may increase the damage risk. Hearing conservation programs should be adopted in the case of routine occupational exposure to higher levels.

It is not yet clear whether the damage risk rules can be extended to the very short durations of impulsive noise. Available evidence indicates that there is an increasing risk when impulsive sound pressure levels reach 130-150 dB(peak). Available evidence also indicates that addition of impulsive noise on a steady noise may increase the risk for damage in the sound pressure level range of 80-110 dB LAeq,8h, and 100-130 dB(peak). It is not yet clear to what extent impulsive noises and low-frequency noises should be given extra consideration in damage risk calculations.

10.5.4 Nonspecific Health Effects

The nonauditory health effects of noise are complex and not yet fully understood. Laboratory and field studies have revealed a variety of physiological reactions such as changes in heart rate, blood pressure and peripheral resistance, and vestibular reactions. Many of these noise-induced reactions are nonspecific and are usually referred to as stress reactions.

Much of the information is based upon animal experiments, many of which have been performed on rodents. These animals differ considerably from human beings in their reactions to noise. Thus, it is very difficult to assess the significance of such experiments for human health and wellbeing.

The possibility cannot be ignored that short-term, and long-term, noise-induced stress, particularly with insufficient time for recovery between periods of work, could increase susceptibility to other work-related diseases, degenerative diseases, and nonspecific diseases that are regarded as consequences of chronic general stress. People normally exposed to hazardous stress during work may be particularly at risk. The reported observations are considered by many to be indications of potential danger to health and have been suspected as predecessors of pathological changes. However, research on this subject has not yielded any conclusive evidence, so far, that disease is caused or aggravated by noise exposure at sound pressure levels insufficient to cause hearing impairment. More epidemiological and animal studies are required to clarify the nature of nonauditory health risks associated with occupational noise exposure.

10.5.5 Interference with Activities

Frequent or severe interruption of various human activities by noise exposure may affect human health and well-being to various degrees. The main interference effects of exposure to occupational noise have been those associated with communication and task performance.

With respect to interference with speech perception, a majority of the population belong to sensitive groups. Most sensitive are persons with impaired hearing. Even slight hearing impairments in the high-frequency range may cause problems with speech perception in a noisy environment. From 40 years of age and up, people demonstrate impaired interpretation ability of difficult, spoken messages with low linguistic redundancy compared to those aged between 20-30 years.

The masking effect of noise exposure on speech communication is well understood and methods are available to calculate word, message, and sentence intelligibility as a function of the characteristics of the masking noise. These methods are widely used in the design of rooms and the specification of background sound pressure level from external and internal noise sources to satisfy communication requirements. Various acoustic engineering reference works give limits of background noise sound pressure levels for various types of rooms such as offices, conference rooms, classrooms, and auditoria. However, it has been noted that communication requirements in industrial situations frequently do not receive adequate attention, particularly with reference to the accident risk. It is vital to be able to hear alarming and informative signals such as door bells, telephone signals, alarm clocks, fire alarms, etc., as well as sounds and signals involved in occupational tasks.

The vast number of experimental data on noise effects on speech discrimination deal with that in lexical terms. The sound pressure level for speech interference starts below 50 dB, maybe even as low as at 30 dB, for octave bands centered to the main speech frequencies of 500, 1,000, 2,000 and 4,000 Hz, when communication distance grows beyond a few meters.

It is usually possible to express the relationship between sound pressure level and speech intelligibility in a single function, based on the assumptions and empirical observations for speaker-to-listener distance of about 1 to 4 m. For the speaker-to-listener distance of about 2 m it can be said:

(1) Speech spoken in relaxed conversation is fairly well intelligible at or below background sound pressure levels of 40-55 dB LAeq but fully intelligible only in background sound pressure levels of less than 45 dB LAeq, and excellently intelligible may be only at or below 30 dB LAeq.

(2) Speech spoken with slightly more vocal effort can be understood only when the background sound pressure level is at or below 50-65 dB LAeq.

For outdoor speech communication, the "inverse square law" applies for sound pressure level of speech over moderate distances, that is, when the distance between speaker and listener is doubled, the sound pressure level of the speech drops by approximately 6 dB. This relationship is applicable to indoor conditions only up to a distance of about 2 m.

Speech communication is affected also by the reverberation characteristics of the room. Already reverberation times less than 1 s can produce loss in speech discrimination. In a quiet environment a reverberation time below 0.6 s is desirable for an adequate speech intelligibility for sensitive groups, maybe 0.25-0.50 s for hearing impaired persons. A longer reverberation time combined with background noise makes speech perception still more difficult and straining.

In cases where speech perception is of paramount importance, for example, in classrooms or conference rooms, or where listeners with impaired hearing are involved, for example, in homes for the elderly, low background sound pressure levels are desirable. To ensure speech comprehension the signal-to-noise relationship should always exceed zero dB.

For sensitive groups or when listening to complicated messages (at school, listening to foreign languages, telephone conversation) the signal-to-noise ratio should be at least 10 dB, preferably 15 dB or more. For sensitive groups this would mean that with a background sound pressure level of 35 dB LAeq, the message level should be at least at 45 dB LAeq, preferably 50 dB LAeq. It follows that in class rooms, one should strive for as low background level as possible.

Task performance interference is complex and depends to a large extent on the nature of the task. It is primarily an occupational problem and there is little evidence that it is significant in situations where noise does not interfere with communication or does not pose a risk of hearing impairment.

Concentration and mental work of all kinds are often assumed to require a quiet environment. However, in spite of some experimental laboratory data, there are no reliable field data to confirm this. No generalized criteria relating task efficiency and noise level or duration in the workplace can be stated.

10.6 Adverse Effects of Community Noise

The health criteria and exposure limits described in the previous section provide guidance for exposure to occupational noise. However, they are of limited use for decisions concerning the environment of the general population. In the latter context, not only adverse health effects have to be considered but also welfare and health promotion.

As is presently the case for occupational noise, measures of equivalent continuous sound pressure level, Leq, for community noise should be qualified with the adequate time interval before guideline values are applied. A common approach is to relate the time integration to the duration of the noise emitting activity (e.g., 8 h of day-time exposure to noise from construction work), another to the duration of the activity of the exposed persons (e.g., the noise exposure during a full night sleep). It should be noted that the equivalence level basically is not fully adequate as a single measure, since most community noise-induced adverse effects are correlated with a combination of several exposure parameters simultaneously, that is:

(1) equivalent level,
(2) maximum level of a noise event,
(3) number of noise events over time, and
(4) time of the day.

With respect to annoyance the method of combining the parameters of noise exposure to an indicator for the observed effect level has been extensively studied. The data are not inconsistent with the simple, physically based equivalent energy theory (however, see Job, 1988a), which is represented by the Leq index, and which in many cases seems to be a fairly acceptable approximation. However, there is a growing concern that all the parameters mentioned above should be assessed in noise exposure investigations, at least in the complex cases.

10.6.1 Populations Affected

Most people are exposed to nonoccupational noise during leisure and rest hours. Community noise may interfere with, and affect the performance of leisure-time activities, causing general annoyance. Leisure activities may also introduce a hearing hazard, for example, by rifle shooting and exposure to loud music in concerts and discotheques. Nonoccupational noise may disturb sleep and rest, and prevent normal performance at home and may, over a period of time, lead to health impairment. Both elderly people, children and individuals with noise-induced hearing loss have difficulties in speech reception in noisy environments (Jokinen, 1973; Elliot, 1979; Dubno, Dirks, & Morgan, 1984; Smoorenburg, 1992). People with reduced adaptability or reserve capacity such as the sick, the aged, people with impaired sleeping functions, or those who are subject to other environmental strains may be particularly vulnerable and in need of special protection against excessive noise exposure.

10.6.2 Hearing Impairment Induced by Community Noise

The knowledge about irreversible effects of moderate noise exposure on human hearing mainly comes from field studies of industrial workers. However, occupational industrial exposure is not the only cause of damage.

Some deterioration of sensory capability is associated with the aging processes per se (presbyacusis). Damage to the sense of hearing may also be caused by certain diseases, some industrial chemicals, ototoxic drugs, blows to the head, and hereditary progressive hearing loss. Rapidly progressive hearing loss with the same audiometric profile as noise-induced permanent threshold shift, but without industrial noise exposure, has been shown. Hearing deficits ascribed to noises of everyday living is defined as sociacusis (Glorig, Grings, & Summerfield, 1958; B. Berglund, U. Berglund, & Lindvall, 1984).

High-level noise exposures that may give rise to noise-induced hearing deficits are by no means restricted to occupational nonindustrial situations. Such levels can also occur in open air concerts, discotheques, motor sports, shooting ranges, and dwellings in terms of noise from loudspeakers or other leisure activities. Other sources are also important such as music played back in headphones, impulse noise from toys and fireworks, noise from domestic lawn mowers, chain saws and food blenders. A study of the real-life noise exposure of teenage children demonstrated that their typical exposure may correspond to the same acoustic energy as is if they had been exposed to a steady noise level of 80-85 dB LAeq (Siervogel, Roche, D.L. Johnson, & Fairman, 1982). It has also been argued that community noise exposure would be a contributing factor to presbyacusis.

For years the emphasis in hearing protection has been only on the more striking hearing losses produced by exposures to noises that are obviously dangerous, that is, those that are so loud that they produce severe temporary hearing losses, and, within few months measurable permanent hearing losses. Compared to a daily industrial exposure of 100 dB LAeq,8h, or more, the additional damage presumably contributed by a sociacusic exposure of 75 or 80 dB LAeq for a few hours a day was thought to be so slight as to be irrelevant. However, with a near-universal adoption of 85 dB LAeq,8h, as a limit for industrial environments, severe exposures at work will occur more rarely. Therefore, the contribution of sociacusic influences to a slow deterioration of auditory sensitivity may no longer be negligible. However, final scientific verification is still lacking.

There is widespread concern about the effect of loud music on young people who frequently attend concerts and, especially, discotheques. The sound level is typically in excess of 100 dB LAeq. This level could lead to significant hearing impairment, especially in later life. Since discotheques may be attended very frequently by the same persons, sometimes authorities require an electronic sound level control above the dancing floor of 85-90 dB LAeq.

Noise exposure for employees of concerts and discotheques should be controlled by established occupational standards. Ideally the same standards should apply to the patrons of these premises as some people may be exposed to intense sound pressure levels from other sources during the day. However, the basis of knowledge for recommending guideline values for patrons is still inconclusive. But the concern for protecting young people's hearing warrants provisional guidelines. It is, therefore, recommended that in concerts patrons should not be exposed to sound pressure levels greater than 100 dB LAeq during a 4-h period. For discotheques, which may be more frequently attended by the same persons than concerts, and each time possibly with a long duration, the sound level preferably should not exceed 90 dB LAeq. In order to remain perceptually attractive for the dancers at this sound level, the electronic equipment and loudspeakers would have to be of a high quality and specifically designed for this purpose. For comparison it should be noted that in order to not exceed occupational hearing protection limits a guideline value of 100 dB LAeq would allow only 1.2 h of exposure in a working week of 40 h.

The same critical effects and guideline values apply for sounds played back in headphones as for exposure to music in concert halls, outdoor concerts, and discotheques. The exposure should not be greater than when converted to equivalent free-field level. It is desired to develop international standards for amplifier output specifications and headphones impedances in portable equipments which guarantee the desired limitation.

To avoid hearing deficits from impulsive sounds, such as from toys and fireworks, performers and audience should not be exposed to more than 140 dB(peak). In order to avoid exposing children to higher sound pressure levels than are allowed, or aimed at, for adults at work, it would be required that the instantaneous sound pressure levels produced by close-to-the-ear toys should not exceed 80 dBA at the position of a child's ear, and for any toy should not exceed 130 dBC(peak) at the position of a child's ear.

10.6.3 Sleep Disturbance

Sleep disturbance due to continuous, as well as intermittent noise, has been demonstrated by electrophysiological and behavioral methods. The more intense the background noise is, the more disturbing is its effect on sleep. Measurable effects start from about 30 dB LAeq. Physiological sleep effects include changes in the pattern of sleep stages, especially a reduction in the proportion of REM-sleep. Subjective effects have also been identified such as difficulties in falling asleep, perceived sleep quality, and adverse after-effects like reported headache and tiredness. The sensitive groups are believed to include mainly elderly persons, shift workers, persons who are especially vulnerable due to physical or mental disorders, and other individuals who have sleeping difficulties.

The probability that sleep will be disturbed by a particular noise depends on a number of factors including the interference criterion used (e.g., awakening or solely EEG changes), the stage of sleep, the time of night, the character of the noise exposure, and adaptation to the noise. Individual differences in sensitivity are pronounced. Although systematically collected field data on sleep disturbance are limited, there is some consensus of opinion that where noise exposure is continuous, the equivalent continuous sound pressure level indoors at night should not exceed approximately 30 dB LAeq if negative effects on sleep are to be avoided.

Low frequency noise, for example, from ventilation systems, can disturb rest and sleep even at low intensity. In the presence of a large proportion of low frequency sounds a still lower value than 30 dB LAeq would be needed. It should be noted that the adverse effect on sleep partly depends on the nature of the noise source.

Sleep disturbance increases with increased maximum sound pressure level. Even if the total equivalent continuous sound pressure level is fairly low, a small number of noise events with a high maximum level will affect sleep adversely. Therefore, guidelines for community noise to avoid sleep disturbance should be expressed not only in terms of equivalent sound pressure level but as maximum levels, and number of noise events during night, as well.

If the noise exposure is not continuous, the maximum sound pressure level is best correlated to sleep disturbances. Effects have been observed at individual exposures of 45 dB LAmax, or even less. It is especially important to limit the noise events exceeding 45 dB LAmax especially where the background sound pressure level is low; in fact, to protect sensitive persons a still lower guideline value would be preferred.

Measures reducing disturbance during the first part of the night can be predicted to be most cost effective. In the first place, efforts should be made to reduce the sound pressure level of noise maxima and the number of noise events before focusing on reducing the equivalent level.

Sleep disturbance is the critical effect in bedrooms, in dwellings and preschools. Recommended guideline values inside bedrooms are 30 dB LAeq for steady-state continuous noise, and for a noise event 45 dB LAmax, preferably even lower, about 40 dB LAmax. Lower sound pressure levels may be annoying depending on the nature of the noise source. The maximum level should be measured with the instrument set at "fast".

At nighttime outdoors, sound pressure levels should not exceed 45 dB LAeq, so that people may sleep with bedroom windows open. This value has been obtained by assuming that the reduction from outside to inside with the window open is 15 dB; note that the actual reduction may be less in some cases, maybe only 5-7 dB, which then would mean that the sound pressure level outdoors needs to be kept at or below 35-37 dB LAeq.

In hospitals sleep disturbance is a main critical effect for most spaces. Alarm signals from instruments may comprise strong narrow-band impulse sounds exceeding 100 dB LAmax. Since patients have less ability to cope with stress, the equivalent continuous sound pressure level should not exceed 35 dB LAeq in most rooms in which patients are being treated, observed or resting. Momentary sounds during nighttime in hospitals should not exceed the equivalent guideline value by more than 10 dBA with the instrument set at "fast". For ward rooms in hospitals during nighttime, the recommended guideline values should be 30 dB LAeq together with 40 dB LAmax. The maximum level should be measured with the instrument set at "fast".

10.6.4 Non-Specific Health Effects

Effects on the systemic circulation such as constriction of blood vessels have been produced under laboratory and field conditions. Many studies have shown blood pressure to be higher in noise-exposed workers and in populations living in noisy areas around airports and on noisy streets than in control populations, while other investigations indicate no blood pressure effects. The overall evidence suggests that a weak association exists between long-term noise exposure and blood pressure elevation or hypertension. Other psychophysiological effects, such as gastrointestinal motility, are less clear. More research is required in order to estimate the long-term cardiovascular and psychophysiological risks due to community noise exposure.

10.6.5 Annoyance

Noise annoyance may be defined as a feeling of displeasure evoked by a noise. The annoyance-inducing capacity of a noise depends upon many of its physical characteristics including its intensity, spectral characteristics, and variations of these with time. However, annoyance reactions are sensitive to many nonacoustic factors of a social, psychological, or economic nature, and there are considerable differences in individual reactions to the same noise exposure. Furthermore, community annoyance varies with activity (speech communication, relaxation, listening to radio and TV, etc.).

Annoyance is affected by the equivalent continuous sound pressure level, the maximum sound pressure level of a noise event, the number of such events over time, and the time of the day. In many cases the simple, physically based equivalent energy measure Leq is a fairly acceptable approximation of exposure. However, there is a growing concern that all the parameters mentioned should be assessed in noise exposure investigations, at least in the complex cases.

Since a large proportion of low frequency components in the noise may increase annoyance considerably, they should be assessed with appropriate octave or 1/3 octave instruments. However, the difference between dBlin (or dBC) and dBA will give a crude information about the contribution of low frequency sounds. If the difference is more than 20 dB, it is recommended to perform a frequency analysis of the noise. It has been proposed tentatively (Lambert & Vallet, 1994) that when the difference between dBC and dBA is 10 dB or more a penalty of 5 dBA should be added for a Leq of less than 60 dBA, and a penalty of 3 dBA for a Leq of 60 dBA or more.

In some instances the combined effects of noise and vibration exposures are of particular importance, for example, with respect to the acceptability of building vibration.

It is easier to get used to noise if the noise is continuous. Habituation is, however, a highly individual matter, as is also the resultant load on the organism exposed to the noise. Generally, it can be said that the load is always involved where possible habituation is disrupted by, for example, a noise peak. Today there is no sufficient basis for a more precise indication of the critical frequencies of noise events. However, it is important to reduce the noise peaks in otherwise uniform noise.

The results of epidemiological questionnaire surveys can be used as guidance concerning the relation between different types of outdoor noise exposure and the extent of annoyance in the community. Available data indicate that daytime sound pressure levels of less than 50 dB LAeq cause little or no serious annoyance in the community. With noise at this sound pressure level, other factors such as transport needs, road safety, and the availability of schools are likely to cause more concern than occasional noise disturbances.

To protect the majority of people from being *seriously annoyed* during the daytime, the sound pressure level from steady, continuous noise on balconies, terraces, and in outdoor living areas should not exceed 55 dB LAeq. To protect the majority of people from being *moderately annoyed* during the daytime, the sound pressure level outdoors should not exceed 50 dB LAeq. Where it is practical and feasible the lower sound pressure level should be considered the maximum desirable sound pressure level for decisions in relation to new development.

Sound pressure levels during the evening and night should be 5 to 10 dB lower than during the day. Again it is emphasized that for intermittent noise it is necessary to take into account the maximum level and the number of noise events over time. Guidelines or noise abatement measures also should take into account the disturbance in residential outdoor activities.

An important problem is the protection of the neighborhood in the surroundings of open air concerts. One way of dealing with the problem might be to limit the sound exposure to the guideline values recommended for dwellings but allowing for a certain limited number of exceptions per year.

Inventories should be made of quiet outdoor areas of any size since it is a prerequisite for far-sighted planning and the preservation of such areas. Large areas should be documented in ”maps of silent resources”. Existing large quiet outdoor areas should be preserved and the background sound-to-noise ratio be kept low.

10.6.6 Interference with Activities

The effects of community noise may be evaluated by assessing interference with different activities. For many community noises, the most important interference seems to be interference with rest/recreation/watching television. There is fairly consistent evidence that noise exposure outdoors above 80 dB LAeq causes reduced helping behavior. Loud noise can also increase aggressive behavior. There is concern that long term exposure to high sound pressure levels of noise could contribute to susceptibility to helplessness in school children.

The effect of noise exposure on the performance of tasks has mainly been studied in the laboratory and, to some extent, in work situations. There have been few, if any, detailed studies of the effects of noise exposure on human productivity in community situations. It is evident that when a task involves auditory signals of any kind, noise exposure at an intensity sufficient to mask or interfere with the perception of these signals will interfere with the performance of the task. There are consistent after-effects of noise exposure on cognitive performance (e.g., proof reading or persistence on challenging puzzles).

Noise can act as a distracting stimulus, depending on how meaningful the stimulus might be, and may also affect the psychophysiological state of the individual. A novel event, such as the start of an unfamiliar noise, will cause distraction and interfere with many kinds of tasks. Impulsive noise (such as sonic booms) may produce disruptive effects as a result of startle responses which may be resistant to habituation.

Performance of tasks involving motor or monotonous activities is not always degraded by noise exposure. But mental activities involving sustained attention to multiple cues, high load in working memory, and complex analytical processes are sensitive to noise exposure. Some accidents may be an indicator of performance deficits as well.

Chronic exposure to noise during early childhood appears to damage reading acquisition. Evidence indicates that the longer the exposure, the greater the damage. Children who have not yet acquired their languages, have demonstrated more adverse effects to intense noise exposures and to long reverberation times than young adults. There is not sufficient information on these effects to set specific guideline values. It is clear, however, that daycare centers, preschools and schools should not be located near major noise sources, such as highways, airports, and industrial sites.

For schools and preschools, the critical effects are speech interference, disturbance of information extraction (e.g., comprehension and reading acquisition), message communication, and annoyance. Studies have shown that the background noise in schools during classes may exceed 51-69 dB and 60-78 dB during 50 and 10 % of the time, respectively (Pekkarinen & Viljanen, 1991), and in day-care centers 68-76 dB and 76-87 dB, respectively (Truchon-Gagnon & Hétu, 1988). However, to be able to hear and understand spoken messages in class rooms, it is recommended that the sound pressure level should not exceed 35 dB LAeq during teaching sessions. For hearing impaired children, a still lower level may be needed; the signal-to-noise ratio should be about 3-4 dB better than for persons with normal hearing. Measurements have shown that the reverberation time in class rooms may range 0.3-1.9 s (250-2,000 Hz; Pekkarinen & Viljanen, 1991) and in day-care centers 0.6-1.6 s (400-2,500 Hz; Truchon-Gagnon & Hétu, 1988). In contrast, it is recommended that the reverberation time in a class room should be about 0.6 s, and preferably lower for hearing impaired children (0.25-0.5 s).

For assembly halls and cafeterias in school buildings, the reverberation time should be less than 1 s. For outdoor playgrounds the sound pressure level from external noise sources should not exceed 55 dB LAeq.

10.7 Summary

Community noise needs to be assessed with respect to risks for both human health and wellbeing. Adverse physiological, biochemical, psychological, sociological and economic consequences of exposure to noise must be critically evaluated for relevant aspects of human behavior, such as work, communication and social interaction, residential activities, recreation and sleep. Intensity, frequency, reversibility and avoidability are pertinent criteria for the severeness of noise effects. Additionally, indices of population response, for example, the percentages or absolute numbers of disturbed people in exposed areas, are relevant figures.

The knowledge about harmful and thus unacceptable impact of noise exposure has to be transformed into environmental standards. As noise protection standards are very consequential, the standard-setting institution must carefully act according to well-defined transparent principles. Furthermore, protective guidelines must consider not only the general population but also subgroups which might be particularly vulnerable. The efficiency of the employed measures should be investigated by evaluation research.

The equivalent continuous sound pressure level basically is not fully adequate as a single measure for community noise, since most community noise-induced adverse effects are correlated with a combination of several exposure parameters, simultaneously, such as, equivalent level, maximum level of a noise event, number of noise events over time, and time of the day. The equivalent measures of sound pressure level, Leq, should be qualified with the applicable time base before guideline values are being applied.

In concerts patrons should not be exposed to sound pressure levels greater than 100 dB LAeq during a 4-h period. For discotheques the sound pressure level preferably should not exceed 90 dB LAeq. The same values would apply for sounds played back in headphones but converted to equivalent free-field sound pressure level. It is desired to develop international standards for amplifier output specifications and headphones impedances in portable equipments which guarantee the desired limitation.

With respect to impulsive sounds, such as from toys and fireworks, performers and audience should not be exposed to more than 140 dB(peak). Even lower limits might be appropriate: the instantaneous sound pressure level produced by close-to-the-ear toys not to exceed 80 dBA at the position of a child’s ear, and for any toy not to exceed 130 dBC(peak) at the position of a child’s ear.

Inside bedrooms the sound pressure level should not exceed 30 dB LAeq for steady-state continuous noise, and for a noise event not exceed 45 dB LAmax, preferably even lower (maybe 40 dB LAmax). Still lower levels may be annoying depending on the nature of the noise source. At nighttime, sound pressure levels outdoors should not exceed 45 dB LAeq, so that people may sleep with bedroom windows open. Even lower levels may be required pending the design of the window opening, maybe 35-37 dB LAeq outdoors.

In residential areas during the daytime, the sound pressure level from steady-state, continuous noise on balconies, terraces, and in outdoor living areas should not exceed 55 dB LAeq, and preferably not exceed 50 dB LAeq. To protect the neighbourhood in the surroundings of open air concerts, the guideline values recommended for dwellings and residential areas should apply but allowing for exceptions a certain number of times per year.

In hospitals the equivalent sound pressure level should not exceed 35 dB LAeq in most rooms in which patients are being treated, observed or resting. Momentary sounds during nighttime should not exceed 45 dB LAmax. For ward rooms during nighttime, the sound pressure level should not exceed 30dB LAeq and 40 dB LAmax.

11 RECOMMENDATIONS

11.1 Guideline Values

[Editors' comments: These guideline values were agreed upon in consensus at the WHO Task Force Meeting in Düsseldorf, Germany, November 24-28, 1992, and have been published in "Executive Summary of the Environmental Health Criteria Document on Community Noise. Copenhagen: World Health Organization, 1993". A number of comments on the recommended Guideline Values have been received by correspondence to the Editors after that Meeting. The Editors have thoroughly evaluated these contributions to the "Recommendations" and, when found appropriate, made them influence the text of Chapter 10 "Evaluation of Health Risks from Exposure to Noise". Thus the readers may find it useful to consult Chapter 10 for supplementary information on Chapter 11.1. However, the latter chapter remains unchanged since it is the outcome in consensus after in depth discussions in the higly qualified Task Force].

The acoustic world around us continuously stimulate the auditory system. The brain selects relevant signals from the acoustic input, but the ear and the lower auditory system are continuously receiving stimuli. This fact does not necessarily imply disturbing and harmful effects. The auditory nerve provides activating impulses to the brain, which enables us to regulate the vigilance and wakefulness necessary for optimum performance. On the other hand, there are scientific reports on harmful effects on humans due to sensory deprivation, which would be the case, if the world around us became completely silent. Thus, it is harmful to have too much sound but also harmful to have too little sound in our environment. Therefore, too, humans should have the right to decide for themselves the quality of the acoustic environment to live in.

By tradition, the exposure to noise from various sources is most commonly expressed as the average sound pressure level over a specific time period, such as 24 hours. This implies that the same average level of chosen time can either consist of a larger number of events with a relatively low, indeed almost nonaudible level, or a few events with a high level. This technical concept does not agree with common experience on how environmental noise is experienced, nor with the neurophysiological characteristics of the human receptor system.

Human perception of the environment through vision, hearing, touch, smell and taste is characterized by a good discrimination of stimulus intensity differences and a decaying sensitivity to a continuous stimulus. Single events can only be discriminated up to a certain threshold, whereafter the exposure is interpreted as continuous. These characteristics are linked to conditions for survival in terms of discrimination of new and different stimuli with low probability and high information value indicating warnings.

Thus, it is relevant to consider the importance of the background level, the number of events, and the noise exposure level independently when assessing the effects of environmental noise on man.

Community noise studies have traditionally considered only noise from a single specific source such as aircraft, road traffic or railway. In recent years, efforts have been made to compare the results from road traffic, aircraft and railway surveys. Data from a number of sources suggest that aircraft noise might be more annoying than road traffic noise which, in turn, might be more annoying than railway noise. But, without a clear understanding of the mechanisms that sometimes creates differences in reactions to different sources, the extent to which the findings from individual studies can be extrapolated to other acoustical environments and community settings is at present unclear.

There may be some populations at greater risk for the harmful effects of noise. Young children (especially during language acquisition), the blind, and perhaps fetuses are examples of such populations. There are no definite conclusions on this topic but the reader should be alerted that guidelines in this report are developed for the population at large and have not addressed the topic of potentially more vulnerable groups.

11.1.1 Specific Effects

11.1.1.1 Interference with communication

Noise tends to interfere with auditory communication in which speech is a most important signal. However, it is also vital to be able to hear alarming and informative signals such as door bells, telephone signals, alarm clocks, fire alarms, etc., as well as sounds and signals involved in occupational tasks. The vast number of experimental data on noise effects on speech discrimination deal with that in lexical terms. Speech interference level starts from below 50 dB SPL for octave bands centered to the main speech frequencies of 500, 1,000, and 2,000 Hz, when communication distance grows beyond a few meters.

It is usually possible to express the relationship between noise levels and speech intelligibility in a single diagram, based on the assumptions and empirical observations that, for speaker-to-listener distance of about 1 m: (a) speech spoken in relaxed conversation is 100 % intelligible in background noise levels of about 45 dBA, and can be understood fairly well in background levels of 55 dBA; and (b) speech spoken with slightly more vocal effort can be understood well, when the noise level is 65 dBA.

With respect to interference with speech perception, a majority of the population belong to sensitive groups. Most sensitive are the elderly and persons with impaired hearing. Even slight hearing impairments in the high-frequency range may cause problems with speech perception in a noisy environment. From 40 years of age and up, people demonstrate impaired ability to interpret difficult, spoken messages with low linguistic redundancy compared to those aged between 20-30 years. It has also been shown that children, before language acquisition has been completed, have demonstrated more adverse effects than young adults to high noise levels and long reverberation times.

For outdoor speech communication, the "inverse square law" applies for speech level over moderate distances, that is, when the distance between speaker and listener is doubled, the level of the speech drops by approximately 6 dB. This relationship is applicable to indoor conditions only up to a distance of about 2 m. Speech communication is affected also by the reverberation characteristics of the room. Already reverberation times beyond 1 s can produce loss in speech discrimination. Even in a quiet environment a reverberation time below 0.6 s is desirable for an adequate speech intelligibility for sensitive groups. A longer reverberation time combined with background noise makes speech perception still more difficult/straining.

In cases where the speech signal perception is of paramount importance, for example, in classrooms or conference rooms, or when listeners with impaired hearing are involved, for example, in homes for the elderly, lower background levels of noise are desirable. To ensure satisfactory speech communication the signal-to-noise relationship should always exceed approximately zero dB.

For sensitive groups or when listening to complicated messages (at school, listening to foreign languages, telephone conversation) the signal-to-noise ratio should be at least 10 dB. This means that in classrooms, one should strive for as low background level as possible. For sensitive groups this would mean that with a background level of 35 dBA, the message should be at least at 45 dBA.

11.1.1.2 Noise-induced hearing loss

High-level noise exposures giving rise to noise-induced hearing deficits are by no means restricted to occupational situations. Such levels can also occur in open air concerts, discotheques, motor sports, shooting ranges, and dwellings in terms of noise from loudspeakers or other leisure activities. Other sources are also important such as music played back in headphones and impulse noise from toys and fireworks. It has also been argued that community noise exposure would be a contributing factor to hearing deficits with increasing age. The existence of such a 'sociocusis' waits for final scientific verification since so many other factors and agents are also influencing hearing.

Hearing disability may be assessed in terms of difficulty in understanding speech. The amount of loss at various speech frequencies has been used as a basis for monetary compensation and varies from one country to another. The unweighted average of the losses, in dB, at 500, 1,000 and 2,000 Hz, that is widely used for assessing noise-induced hearing impairment is somewhat misleading since noise-induced hearing deficits usually occur at 2,000 Hz and above. Commonly, frequencies of 3,000, 4,000 and 6,000 Hz are also included in damage assessment formulae.

There is some disagreement concerning the relationship between the relative ear-damaging capacity of the noise level and its duration. However, the hypothesis that the hearing damage associated with a particular noise exposure is related to the total energy of the sound (i.e., the product of intensity and time) is used for practical purposes. Thus, from a hearing-deficit point of view, noise is primarily described in terms of equivalent continuous sound pressure level, Leq, measured in dBA. For occupational noise, the sound pressure level is usually averaged over the entire 8-h shift (LAeq, 8h), and 40 h per week.

Available data show that there is considerable variation in human sensitivity with respect to hearing impairment. The hazardous nature of a noisy environment is therefore described in terms of "damage risk". This may be expressed as the percentage of people exposed to that environment who are expected to suffer noise-induced hearing impairment after appropriate allowance has been made for hearing losses due to other causes, mainly aging. It is generally believed that this risk is negligible at noise exposure levels of less than 75 dB LAeq, 8h, but increases with increasing levels. The threshold value below which noise can damage hearing, may be even lower due to the exposure combined with intake ototoxic drugs and chemicals.

It is not yet clear whether the damage risk rules can be extended to the very short durations of impulsive noise. Available evidence indicates that an increasing risk exists, when impulsive sound pressure levels reach 130-150 dB(peak). Available evidence also indicates that addition of impulsive noise on a steady noise increases the risk for damage. It is not yet clear to what extent extra consideration should be given to impulse noises and low-frequency noises in damage risk calculations.

11.1.1.3 Sleep disturbance effects

Sleep disturbance due to continuous, as well as intermittent noise, has been demonstrated by electrophysiological and behavioral methods. The more intense the background noise is, the more disturbing is its effect on sleep. Measurable effects start from about 30 dB LAeq. Physiological sleep effects include changes in the pattern of sleep stages, especially a reduction in the proportion of REM-sleep. Subjective effects have also been identified such as difficulties in falling asleep, subjective sleep quality, and adverse after-effects like headache and tiredness. The sensitive groups will mainly include elderly persons, shift workers, persons who are especially vulnerable due to physical or mental disorders, and other individuals who have sleeping difficulties.

Sleep disturbance increases with increased maximum noise level. Even if the total equivalent noise level is fairly low, a small number of noise events with a high maximum sound pressure level will affect sleep. Therefore, guidelines for community noise to avoid sleep disturbance should be expressed in terms of equivalent sound pressure level of the noise as well as maximum levels, and number of noise events. It should be noted that the low frequency noise, for example, from ventilation systems, can disturb rest and sleep even at low sound pressure level.

Where noise is continuous, the equivalent sound pressure level should not exceed 30 dBA indoors, if negative effects on sleep are to be avoided. In the presence of a large proportion of low frequency noise a still lower guideline value is recommended. It should be noted that the adverse effect of noise partly depends on the nature of the source.

If the noise is not continuous, the maximum level is best correlated to sleep disturbances. Effects have been observed at individual exposures of 45 dBA or even less. It is especially important to limit the noise events exceeding 45 dBA where the background level is low; to protect sensitive persons a still lower guideline value would be preferred.

Measures reducing disturbance during the first part of the night are believed to be most effective for the ability of falling asleep. *In noise exposure control, one should consider at the same time the equivalent sound pressure level, the levels of the noise peaks and the number of noise events.*

11.1.1.4 Cardiovascular and psychophysiological effects

Effects on the systemic circulation such as constriction of blood vessels have been observed under laboratory and field conditions. Many studies have shown blood pressure to be higher in noise-exposed workers and in populations living in noisy areas around airports, and on noisy streets than in control populations, while other investigations indicate no blood pressure effects. The overall evidence suggests that a weak association exists between long-term noise exposure and blood pressure elevation or hypertension. Other psychophysiological effects, such as gastrointestinal motility, are less clear. More research is required in order to estimate the long-term cardiovascular and psychophysiological risks due to noise. In view of the equivocal findings, no guideline values may be given.

11.1.1.5 Performance effects

The effect of noise on the performance of tasks has mainly been studied in the laboratory and to some extent in work situations, but, there have been few, if any, detailed studies of the effects of noise on human productivity in community situations. It is evident that when a task involves auditory signals of any kind, noise at an intensity sufficient to mask or interfere with the perception of these signals will interfere with the performance of the task. There are consistent aftereffects of noise on cognitive performance (e.g., proof reading, persistence on challenging puzzles).

Noise can act as a distracting stimulus, depending on how meaningful the stimulus might be, and may also affect the psychophysiological state of the individual. A novel event, such as the start of an unfamiliar noise will cause distraction and interfere with many kinds of tasks. Impulsive noise (such as sonic booms) may produce disruptive effects as the result of startle responses which are more resistant to habituation.

Performance of tasks involving motor or monotonous activities is not always degraded by noise. Mental activities involving sustained attention to multiple cues, high load in working memory, and complex analytical processes are sensitive to noise. Some accidents may be an indicator of performance deficits as well.

Chronic exposure to noise during early childhood appears to damage reading acquisition. Evidence indicates that the longer the exposure, the greater the damage. There is no sufficient information on these effects to set specific acoustic guideline values. It is clear, however, that daycare centers and schools should not be located near major noise sources, such as highways, airports, and industrial sites.

11.1.1.6 Annoyance responses

Noise annoyance may be defined as a feeling of displeasure evoked by a noise. The annoyance-inducing capacity of a noise depends upon many of its physical characteristics including its sound pressure level, spectral characteristics, and variations of these properties of noise with time. However, annoyance reactions are sensitive to many non-acoustic factors of a social, psychological, or economic nature and there are considerable differences in individual reactions to the same noise.

Annoyance is affected by the equivalent sound pressure level, the highest sound pressure level of a noise event, the number of such events, and the time of the day. Method for combining these effects have been extensively studied. The data are not inconsistent with the simple, physically based equivalent energy theory, which is represented by the Leq noise index.

Community annoyance varies with activity (speech communication, relaxation to ratio and TV, etc.). The threshold of annoyance for steady-state, continuous noise is around 50 dB LAeq. Few people are seriously annoyed during the day time at noise levels below around 55 dB LAeq. Noise levels during the evening and night should be 5 to 10 dB lower than during the day. It is emphasized that for intermittent noise it is necessary to take into account the maximum sound pressure level and the number of noise events. Guidelines or noise abatement measures also should take into account residential outdoor activities.

11.1.1.7 Effects on social behavior

The effects of environmental noise may be evaluated by assessing interference with different activities. For many community noises, the most important interference seems to be interference with rest/recreation/watching television. There is fairly consistent evidence that noise above 80 dBA causes reduced helping behavior. Loud noise also increases aggressive behavior in individuals predisposed to aggressiveness.

There is concern that exposure to high levels of chronic noise could contribute to susceptibility to helplessness in school children. Guidelines on these issues must await further research.

11.1.2 Specific Environments

A noise measure based only on energy summation expressed as the conventional equivalent measure, LAeq, is not enough for the characterization of most noise environments. It is equally important to measure and display the maximum values of the noise fluctuations, preferably combined with a measure of the number of noise events. If the noise includes a large proportion of low frequency components, still lower values than the recommended guideline values below will be needed.

Where prominent low-frequency components are present, they should be assessed with appropriate octave or 1/3rd octave instruments. However, the difference between dBlin (or dBC) and dBA will give crude information about the contribution of low frequency sounds. If the difference is more than 20 dB, it is recommended to perform a frequency analysis of the noise. It should be noted that a large proportion of low frequency components in the noise may increase considerably the adverse effect.

[Editors' comments: The following equivalent measures, LAeq,T, should be qualified with the applicable time base before the guideline values are being applied.]

11.1.2.1 Dwellings

For dwellings the critical effects are sleep disturbance, annoyance and speech interference. Specifically, for bedrooms the critical effect is sleep disturbance. Recommended guideline values for bedrooms inside are 30 dB LAeq for steady-state continuous noise and 45 dB LAmax. Lower levels may be annoying depending on the nature of the noise source. The maximum sound pressure level should be measured with the instrument set at "fast". To protect the majority of people from being seriously annoyed during the daytime, the sound pressure level from steady, continuous noise on balconies, terraces, and in outdoor living areas should not exceed 55 dB LAeq.

To protect the majority of people from being moderately annoyed during the daytime, the noise level should not exceed 50 dB LAeq. Where it is practical and feasible the lower noise level should be considered the maximum desirable noise level for decisions in relation to new development.

At nighttime outside noise levels should not exceed 45 dB LAeq, so that people may sleep with bedroom windows open. This value has been obtained by assuming that the noise reduction from outside to inside with the window open is 15 dB.

11.1.2.2 Schools and preschools

For schools, the critical effects are speech interference, disturbance of information extraction (e.g., comprehension and reading acquisition), message communication, and annoyance. To be able to hear and understand spoken messages in class rooms, the noise level should not exceed 35 dB LAeq during teaching sessions. For hearing impaired children, a still lower sound pressure level may be needed. The reverberation time in the class room should be about 0.6 s, and preferably lower for hearing impaired children.

For assembly halls and cafeterias in school buildings, the reverberation time should be less than 1 s. For outdoor playgrounds the sound pressure level of the noise from external sources should not exceed 55 dB LAeq .

For preschools, the same critical effects and guideline values apply as for schools. In bedrooms in preschools during sleeping hours, the guideline values for bedrooms in dwellings replace those of schools.

11.1.2.3 Hospitals

For most spaces in hospitals, the critical effects are sleep disturbance, annoyance, and communication interference, including warning signals. Since patients have less ability to cope with stress, the equivalent sound pressure level should not exceed 35 dB LAeq in most rooms in which patients are being treated, observed or resting. Attention should be given to the noise levels in intensive care units and operating theaters. Guideline values must await future research.

Momentary sounds during night time should not exceed the guideline value recommended for equivalent noise by more than 10 dBA with the instrument set at “fast”. For ward rooms in hospitals, the recommended guideline values should be 30dB LAeq, together with 40 dB LAmax. The maximum level should be measured with the instrument set at “fast”.

11.1.2.4 Concert halls, outdoor concerts and discotheques

There is widespread concern about the effect of loud music on young people who frequently attend concerts and, especially, discotheques. The sound pressure level is typically in excess of 100 dB LAeq. Such a noise exposure could lead to significant hearing impairment, especially in later life.

Noise exposure for employees of this venues should be controlled by established occupational standards. Ideally the same standards should apply to the patrons of these premises as some people may be exposed to high noise levels from other sources during the day. However, the basis for recommending guideline values for patrons is still inconclusive. But the concern for protecting young people’s hearing warrants provisional guidelines. It is therefore recommended that patrons should not be exposed to sound pressure levels greater than 100 dB LAeq during a 4-h period.

11.1.2.5 Sounds played back in headphones

The same critical effects and guideline values apply for sounds played back in head-phones as for exposure to music in concert halls, outdoor concerts, and discotheques. The exposure should not be greater than when converted to equivalent free-field level.

11.1.2.6 Impulsive sounds from toys and fireworks

To avoid hearing deficits, performers and audience should not be exposed to more than 140 dB(peak). The instrument should be set at "impulse".

11.1.2.7 Outdoors in parkland and conservation areas

Existing large quiet outdoor areas should be preserved and the signal-to-noise ratio kept low.

11.2 Research and Development Needs

In the following examples are given of identified and essential research and development needs, in nonprioritized order.

Measurement and methods:

(1) Effect-related noise measures and indices which refer to specific effects on people.

(2) Accurate and comparable measures of individual annoyance responses in order to permit validation of noise metrics.

(3) Create a database of measurements for all possible noise sources expressed in loudness, sharpness and roughness values, in order to obtaine new types of guideline values for noise annoyance.

Source characterization and comparison:

(1) Comparison of effects on people of various community noises characterized with respect to time, pattern of events, spectral composition, etc.

(2) Comparison of impulsive and non-impulsive noise effects, in order to understand the important differences.

Exposure assessment:

(1) Methods for forecasting population noise exposures from knowledge of noise source emissions.

(2) Rules and phenomena of noise propagation around buildings.

(3) Exposure limits for different community environments.

(4) An international expert system for practical guidance on noise impact and abatement assessment.

(5) Careful and complete characterization of individual noise exposure (preferably at home, work, and during commuting).

Auditory effects:

(1) Field studies on auditory effects of exposure to specific sounds such as aircraft noise and loud music, including effects such as noise-induced temporary and permanent threshold shifts, speech perception and misperception, tinnitus and information retrieval.

(2) Protocols for reliable measurements of high-frequency hearing (8,000 Hz and above) and evaluation of such measures as early biomarkers for hearing loss.

Sleep disturbances:

(1) Influence of noise-induced sleep disturbances on health, work performance, accident risk and social life, including exposed (sensitive) groups and long-term effects of exposure to noise.

(2) How physiologically and perceptually assessed sleep quality relate to the number of noise events per night exceeding a certain level of the sleep-stages, and of the aftereffects.

(3) Relationship between psychosocial symptoms and reduced perceived sleep quality.

Other physiological effects:

(1) Prospective longitudinal studies of community noise that examine physiological measures of health including standardized health status inventory, blood pressure, neuroendocrine and immune function.

(2) Significance of annoyance to physiological effects of noise.

(3) Nonauditory responses of individuals to long-term, moderately high as well as extremely high noise exposures, including the mitigating effect of individual hearing protector use on blood pressure and the cardiovascular and immune systems, and the time-to-onset relationship for noise-induced hypertension.

(4) Perception of control of noise exposure, genetic traits, coping strategies and noise annoyance as modifiers of the effect of noise on the cardiovascular system and as causes of individual variability in response to noise.

Mental health effects:

(1) Community noise-induced psychiatric disorders inventory, especially with respect to their relation to perception and experience of sound.

(2) Determination, e.g., by longitudinal studies, the form of the causal connection between mental health effects and annoyance.

Dose-response information:

(1) Dose-response relationships for various effects and continuous community noise at relatively low levels of exposure and low number of noise events per time unit.

(2) General form of dose-response relationships for moderate, as well as, high annoyance reactions by analyses of readily available existing social survey data.

(3) Dose-response information on various effects of low-frequency, continuous noise at relatively low levels of exposure.

(4) Examine dose-response relationships for adverse subjective effects other than annoyance, for example, dissatisfaction, disappointment and mood changes.

(5) Examine the effects of psychological variables in predicting reaction, and especially determine the direction of causality.

Interactions:

(1) Interacting effects with respect to source as well as effect interaction, including possible impact on auditory changes of interacting combinations of noise exposure and exposure to chemical agents.

(2) Optimal solutions/guidelines for the interaction of noise with other load factors.

Habituation and coping:

(1) Connection between noise characteristics and the habituation and coping potential, including humans' coping capabilities and strategies, and habituation/dishabituation processes in different situations.

(2) Measures for facilitating ethically justifiable habituation and coping to various components of different types of noise and various situations.

(3) Characterization of good "restoration areas" which provide possibility for rest without any adverse noise load.

Risk groups:

(1) Identification of potential risk groups, including identification of sensitive individuals, differences between sexes, distribution of risk among age groups, and influence of sounds on pregnancy course and on fetal development.

Costs and cost effectiveness:

(1) Economic indices for adverse noise effects including changes in productivity, accidents, use of health care system and behavioral changes.

(2) Effectiveness of sound insulation (or active noise absorption), especially in residential buildings, for reducing long-term annoyance by studying sites which provide data on remedial activities and change in behavioral patterns among occupants.

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APPENDIX I:

NOISE EXPOSURE AND EFFECT CONTROL

Noise levels in the environment can be reduced or limited by emission control, which should be aimed at noise sources contributing most to the effects experienced by man. The relevant sources are not always those that contribute most to the total dose from an acoustic point of view. Environmental noise control can be implemented by the use of environmental noise standards. These standards can be met by control at the source, by limiting the number of sources, by the physical separation of noise sources and people, and by changes in work methods. The technological background and information on dose-response relationships for both environmental and industrial noise are sufficient to allow appropriate action to be taken and to predict the effectiveness of noise abatement programs.

The control of environmental noise requires the participation of local health authorities and interested organizations. As problems caused by environmental noise, such as aircraft and traffic noise, are mostly due to mistakes in planning policies, it may be difficult to put a sufficiently stringent noise abatement program into action in built-up areas. Care should therefore be taken that planning programs include all long-term noise control measures which may be necessary.

Action concerning specific sources of noise such as cars or aircraft, often has to be taken at an international level using long-term planning strategy as a background.

There are data which suggest that exposure to noise during leisure time in certain cases may constitute a risk to hearing in some segments of the general population. Noise from electronic music, discotheques, home power tools, guns, and certain other sports equipment might cause hearing impairment. These hearing losses occur primarily in young people, frequently prior to their occupational exposure. Hazardous noise exposures during leisure time should be controlled through consumer product control, noise labeling of products, environmental noise limits, and public education. Ear protection should be recommended in conjunction with equipment producing hazardous noise levels.

1 Engineering Control

1.1. Physical Planning

In most countries, land-use planning and zoning is used to avoid conflicts between noise sensitive buildings and noise-generating installations such as airports, railways, roads and industrial plants (OECD, 1991). Long-term quality objectives are often prescribed comprising a maximum permissible level and a preferred noise level, the latter to be used as the basis for future planning.

1.2 Source Replacement and Modification

The most efficient action against excessive noise is the reduction of the noise at source. There are rules in different countries and within the European Communities on permissible noise emissions from motor vehicles, aircrafts, construction vehicles, and household and garden equipments. In industry, noise control technology is available for solving many typical noise problems arising from the use of machinery. Usually the most effective approach is to redesign or replace noisy equipment, processes, or materials. If this is not possible, significant reductions in noise levels can be achieved by structural and mechanical modifications, or the use of mufflers, vibration isolators, and noise protection enclosures (Beranek, 1971, see also 1988).

The noise radiated from a machine and transmitted through structure-borne connections very much depends on the materials used. The mechanics of sound wave generation may differ in two main categories between noise sources. One is surface motion of a vibrating solid and the other is turbulence in a fluid medium. One of the first steps for noise control should be the reduction of forces and flow velocity that create noise generating vibrations. Some materials have a high internal damping while others not. In the latter case noise can be reduced by applying damping of the material (Berger, Ward, Morrill & Royster, 1986).

Control at the source may aim at reducing driving force, response and area of vibrating surface, modified reduced directivity of the source, and reduced velocity of fluid flow.

1.3 Path Modification

A further reduction in noise can be obtained by increasing the distance between people and the noise source. For example, this can be achieved in the community by planning the location of transport facilities and, in industry, by the careful selection of work sites. Sound transmission can also be controlled by the use of partitions or barriers, e.g., for traffic noise along streets or, in industry, around particularly noisy or disturbing machinery. Reverberant noise levels can be reduced by sound-absorbing materials. The techniques for the control of sound propagation and transmission are well developed (Beranek, 1971, see also 1988).

2 Administrative Means

Governmental administrative means to reduce noise involve five kinds of function (OECD, 1991). Planning involves decision on the future use of resources, guidance and coordination, etc. Regulating defines the rules of the game. Enforcement of regulation is being made by supervision to ensure compliance with laws and regulations. Incentives include economic and non-economic measures to persuade public or private parties concerned. Investment including allocation of public funds for infrastructure, equipment, research.

In practice the objectives of noise abatement policies are rarely explicit and quantified. The coordination is frequently inadequate and there is a frequent imbalance in government action (OECD, 1991).

2.1 Environmental Guidelines

2.1.1 Aircraft noise

The major policies used to reduce aircraft noise include emission limits for engine noise, variable noise charges as a component of landing fees, traffic management including time and rout limitations for noisy aircraft, land-use planning, and sound insulation of dwellings and installation of barriers. Many countries are implementing noise-level limits for aircraft based on noise standards of the International Civil Aviation Organization (ICAO, 1993). The limit values for individual aircraft during take-off and landing are specified in terms of Effective Perceived Noise Levels (EPNL) and depend on the weight of the aircraft and the number of engines. At major airports time restrictions for aircraft operations are implemented roughly between 23:00 and 06:00.

2.1.2 Railway noise

There are no emission limits for trains but suggestions have been given for acceptable noise-exposure criteria for nearby dwelling (Walker, 1988). Clearly acceptable levels would be in daytime 60-65 dBA and in nighttime, if necessary, 60 dBA. A tolerable level in daytime is suggested to be 70 dBA.

2.1.3 Industrial noise

Maximum permissible noise load for industrial noise in nearby areas differ somewhat between countries (e.g., Australia, Switzerland, Germany, Japan & The Netherlands). For noise sensitive zones (schools & old peoples homes), the maximum levels is 30-55 dBA, for mainly residential zones 30-60 dBA, and for commercial and industrial zones 50-65 dBA (OECD, 1991).

2.1.4 Road traffic noise

Reduction of road traffic noise can be achieved through reduction of noise at source and of noise transmission through improved traffic management, and by control of receptor noise levels through non-vehicular measures, (land-use planning, roadside noise barriers, insulation in residential areas, and improvement of road surfaces).

The planning noise levels for insulation of dwellings against road traffic noise varies by country (e.g., Japan, Australia, France Germany &

The Netherlands), at dwelling frontages between 52 and 65 dBA. In France, buildings exposed to over 60 dBA are eligible for insulation grants.

2.2 Occupant and Consumers Equipment Modifications

A means of creating low noise products is labeling which provides standardized information on product noise emission levels. By doing so, consumer awareness will increase and create a stimulus for manufacturers to develop low-noise products. There are four main prerequisites for making labeling successful (OECD, 1991). (1) A legal obligation to provide noise labels. (2) An easily identifiable label. (3) A standardized system of acoustic verification. (4) Awareness on the part of consumers, occupants, and workers. Such labeling has been used or discussed for lawn mowers, construction equipment, and power tools.

2.3 Work Place Organization

A reduction in the length of exposure can be used in industry to supplement the previous measures, if necessary. This may be accomplished by job rotation or by restricting the operation of the noise source.

Pre-employment and follow-up audiometric examinations should be included in a hearing conservation program. They provide opportunities for the detection of persons threatened by the development of NIPTS in order to take preventive action. Audiometric tests are also helpful in monitoring the effectiveness of ear protection and of noise abatement programs. The examinations should be performed by qualified technicians under the supervision of physicians or health officials. It is usually accepted that the measurement of pure-tone air conduction thresholds is sufficient for this purpose. However, it should be stressed that periodical checks on equipment calibration, background noise levels in testing rooms, and audiometric procedures are necessary to minimize measurement errors. The frequency of follow-up audiometric tests is, in principle, dictated by the type and level of noise exposure. A general rule for audiometric testing is to wait at least 16 h after the last noise exposure to allow recovery from NITTS.

Whenever noise exposures are such that an unavoidable risk of permanent hearing loss exists, occupational health services should provide for a hearing conservation program. Such programs, for which detailed guidelines exist, contain three elements: education concerning the hazards of noise; education in the proper use and supervision of the wearing of ear protection; and monitoring audiometry including periodical medical examination, when necessary. Monitoring audiometry, if properly planned and executed, will identify workers at risk from incipient hearing impairment, so that they can be removed from the noisy workplace before irreversible damage is caused.

Since present occupational noise standards in most countries allow a certain risk of permanent hearing loss, a hearing conservation program is usually highly advisable in addition to the specification of maximum exposure levels. Hearing conservation programs are considered desirable when 8-h daily exposures exceed 75 dBA. Present concepts of acceptable risk and economic constraints limit their practical application in most countries to levels around 85 dBA.

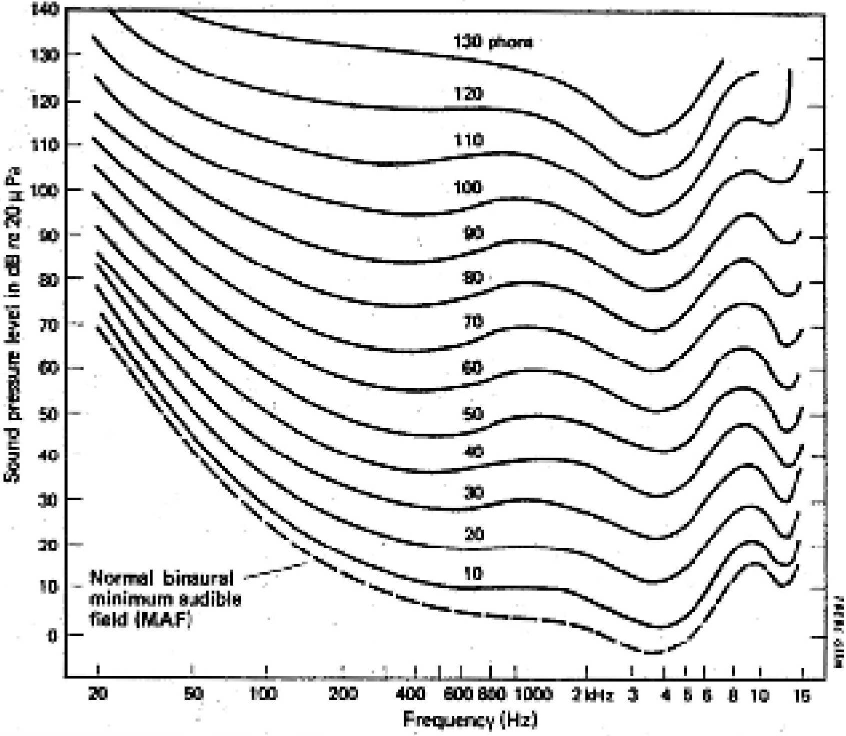
3. Other Means

3.1 Hearing Protection Devices

Hearing protectors are the least desirable option from the standpoint of preventing damage. However, if it is absolutely impossible to reduce noise to a harmless level then some form of hearing protection device (i.e., ear-plug, ear-muffs, and/or helmets) is necessary. Most protectors on the market are supposed to be designed to provide an overall reduction in exposure of about 15 to 30 dB, depending on the brand (Berger, 1993). Therefore, when the use of personal ear protection is necessary, attention must be given to usage, hygiene, discomfort, allergic reactions, and other medical problems that may arise through their use; and the means for ensuring proper, diligent and effective use. The reason is that the protectors leak noise if they are worn imperfectly or are damaged, Unfortunately, many workers use hearing protectors inconsistently or improperly. Furthermore, ear plugs are impractical in dirty or oily situations and can end up transferring the grime or frease into the during insertion. Others workers find ear muffs uncomfortable, especially in warm weather. In this context it is important to provide quiet facilities (quite room) and the opportunity for the temporary removal of ear protectors by those working in high noise levels. Finally, it must be noted that the commonly held view that ear protectors interfere with communication is incorrect, at least in continuous, high-level noise, the reverse is often found to be the case.

3.2 Educational and Information Programs

It is vitally important that persons who face a risk of exposure to potentially hazardous noise levels should be educated in: (a) the possible consequences of excessive noise exposure; (b) the means of protection; and (c) the limitations of these means (e.g. improper use of ear-muffs).



130 phons
120
110
100
90
80
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Normal binaural minimum audible field (MAF)
Sound pressure level in dB re 20 μ Pa
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130
120
110
100
90
80
70
60
50
40
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2 kHz
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Frequency (Hz)

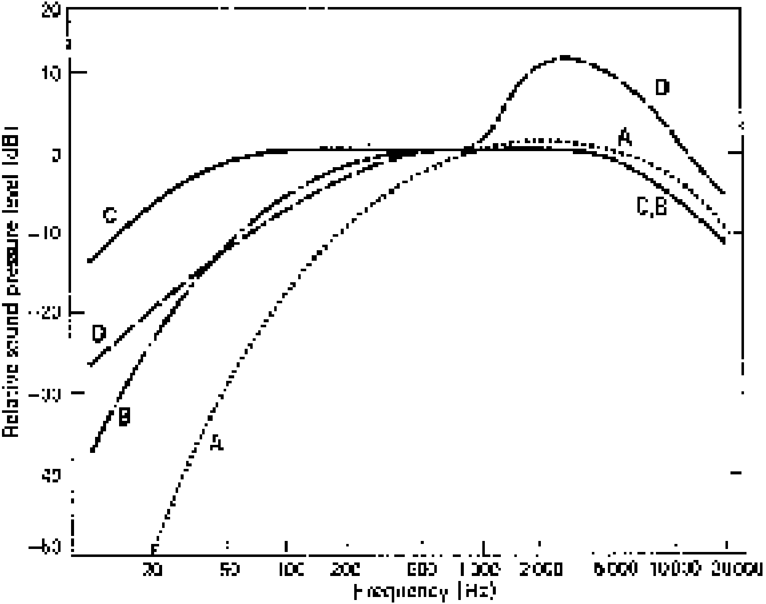

Figure 2. Standard A, B, C, and D filter characteristics for sound level meters (IEC 179, 1973a; IEC 179a, 1973b).

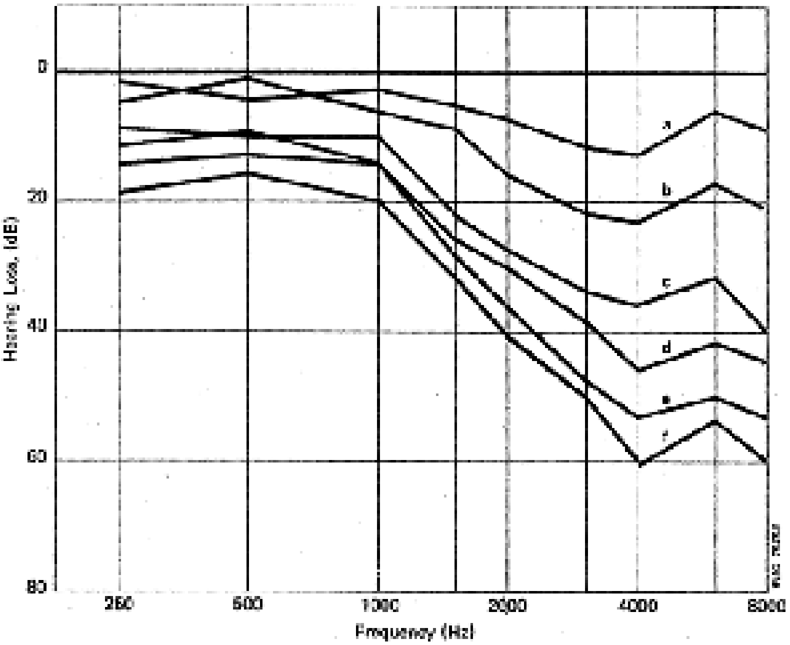

Figure 3. Hearing loss as a function of duration in noise exposure in years. Mean audio-grams for 203 miners, best ear tested. (a <1 year; b = 1-5 years; c = 6-10 years; d = 11-20 years; e = 21-30 years; f > 30 years. From: B. Johansson, 1952.)

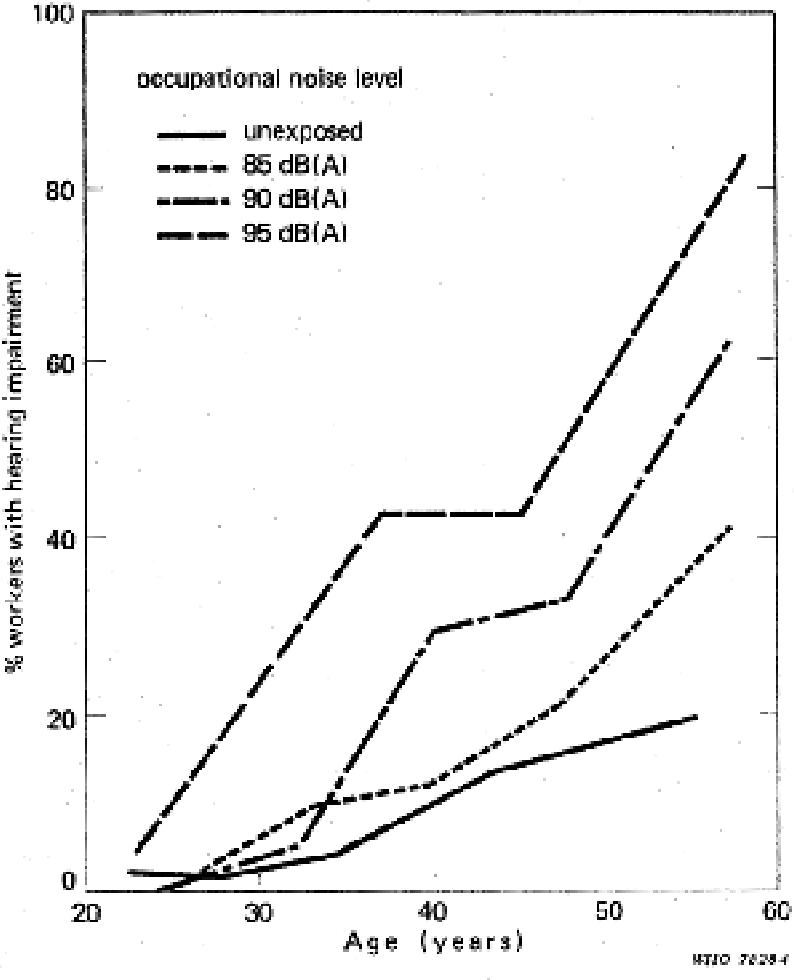

Figure 4. Percentage of workers with hearing impairment (average hearing loss at 1, 2, and 3 kHz >25 dB) [*From*: US National Institute for Occupational Safety and Health (Lampert & T.L. Henderson, 1973)].

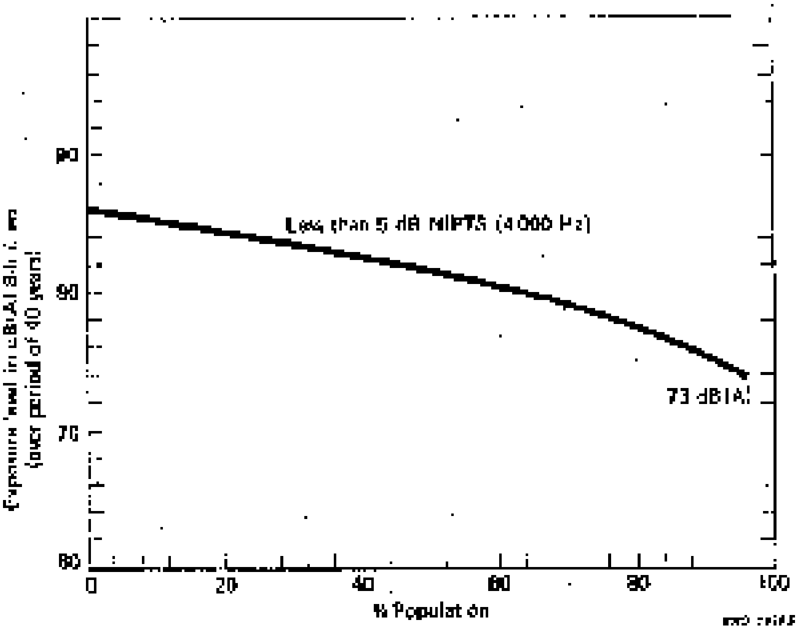

Figure 5. Percentage of exposed population that will incur no more than 5 dB NIPTS shown as a function of exposure level. Population ranked by decreasing ability to hear at 4,000 Hz. [US EPA, 1974b].

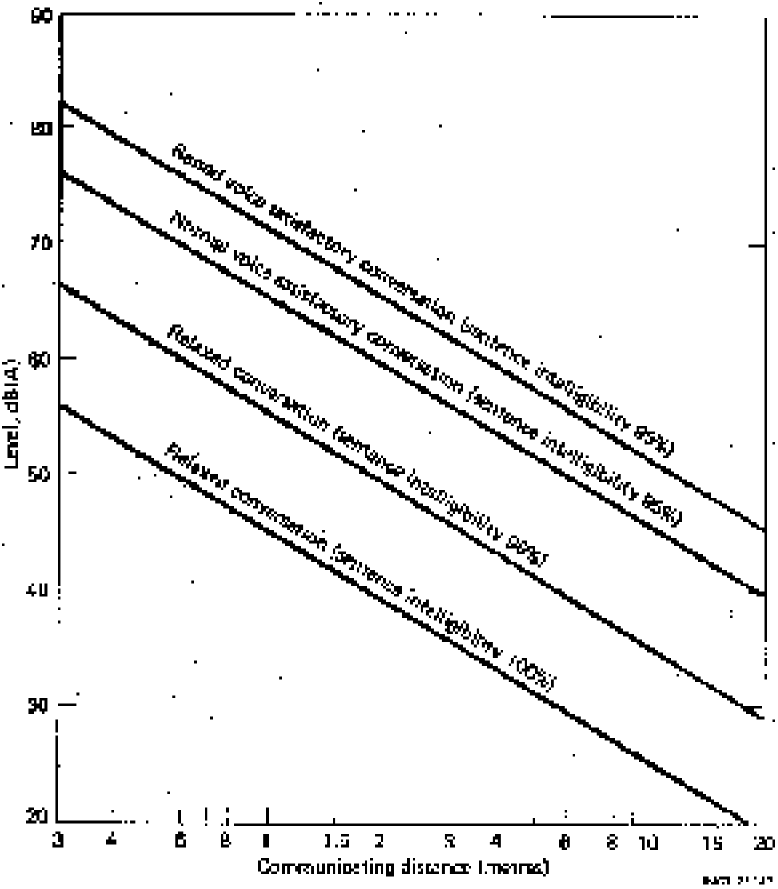

Figure 6. Maximum distances outdoors over which conversation is considered to be satisfactory intelligible in steady noise (U.S. EPA, 1974b).

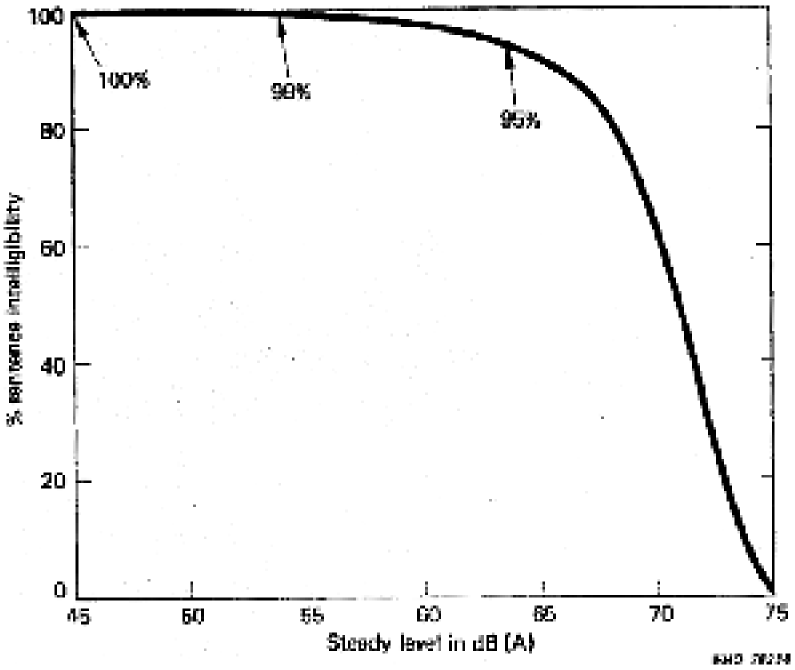

Figure 7. Normal voice intelligibility as a function of the steady background sound level in a typical living room (U.S. EPA, 1974b).

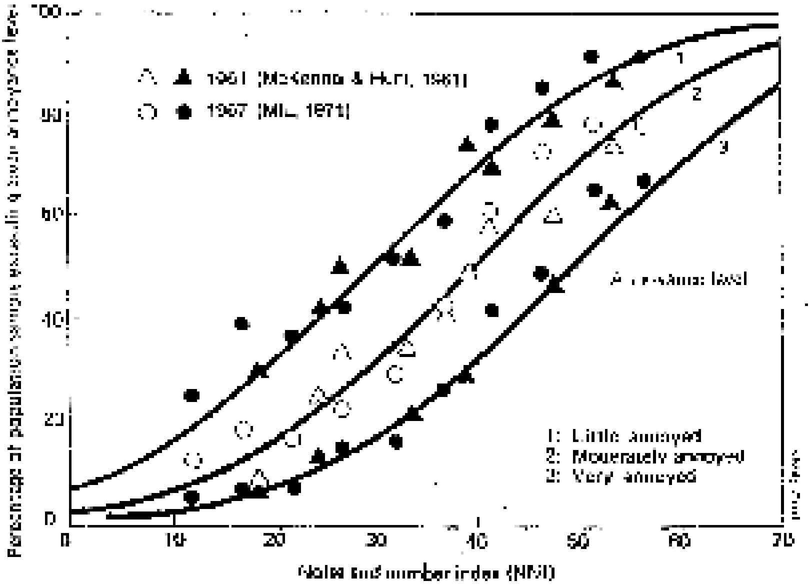

Figure 6. Normal distribution of annoyance scores (Ollerhead, 1973).

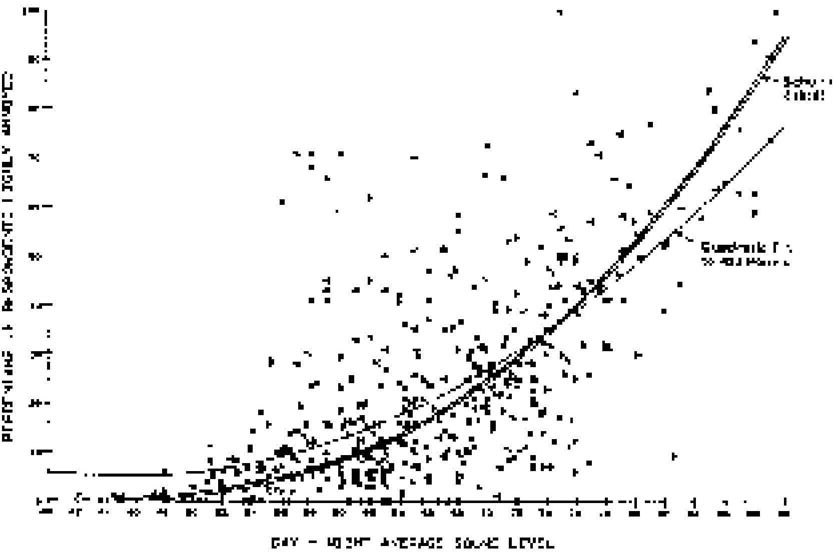

Figure 9. Percentage of respondents highly annoyed as a function of exposure to general transportation noise (day-night average sound level in dBA Ldn). Least squares quadratic fit to 453 data points of 27 epidemiological community surveys. The third-order polynomial fitting function of 161 of the data points by Schultz (1978) is also shown (double line). (From Fidell, Barber, & Schultz, 1991).