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Adverse effects of noise exposure on health
a state of the art summary

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Abstract

This document is prepared by order of the Department of Technology Assessment of the University of Stuttgart, within the framework of UNITE (UNification of accounts and marginal costs for Transport Efficiency). Within the UNITE program, exposure-effect relationships are needed for a monetary valuation of transportation noise. The aim of this project is to give an overview of the state-of-the-art of noise effects research and to provide an overview of exposure-effect relationships. Available exposure-effect relationships are given for the effects of transportation noise on various health aspects in the living environment, in offices and other otherwise quiet working environments and recreational areas. Some of these relationships are well established, others are of a preliminary nature. In addition, an estimate of the importance and occurrence of different types of effects in the Netherlands is given. With respect to disturbances during outdoors recreation, results of a number of investigations carried out in National Parks in the United States are reviewed. However, it is uncertain whether these relationships can be applied in Europe, where conditions are different.

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1 Introduction

This document is prepared by order of the Department of Technology Assessment of the University of Stuttgart, within the framework of UNITE (UNification of accounts and marginal costs for Transport Efficiency). Within the UNITE program, exposure-effect relationships are needed for a monetary valuation of transportation noise. This study aims to give an overview of the state-of-the-art of noise effects research. The main focus is to produce a list describing the currently available exposure-effect relationships for the effects of transportation noise on health. In addition, the document gives an estimate of the importance and occurrence of different types of effects in the Netherlands.

When addressing the issue of adverse effects on health, the term health needs to be defined first. 'Health effect' is defined by the WHO document 'Guidelines for community noise' (1999) as:

"an adverse effect of noise is defined as a change in the morphology and physiology of an organism that results in impairment of functional capacity, or an impairment of capacity to compensate for additional stress, or increases the susceptibility of an organism to the harmful effects of other environmental influences".

Health effects are diverse. When characterizing effects both acute (temporary) and long lasting effects can be distinguished, some of the latter being permanent.

There is sufficient scientific evidence that exposure to noise can lead to adverse health effects. This insight is not new. A large number of effects of noise exposure on health and quality of life were already known or at least hypothesized in the 1960's. Since then, a large number of epidemiological studies have been carried out that have confirmed and refined earlier insights. Currently a large variety of scientific information is available on a wide range of noise effects.

In general, exposure specified by the environment in which persons are exposed includes four categories:

- 1 exposure in the living environment (including schools);
- 2 exposure in the working environment;
- 3 exposure during leisure time;
- 4 exposure during transportation.

In the living environment the main sources of noise include road traffic, rail traffic, air traffic, industry and neighbourhood activities. Noise sources in the working environment depend largely on the kind of activities and may be generated both within and outside the workplace. The main sources of noise in the living environment may also have an impact on office workers and other people during working hours if the sounds enter their otherwise quiet work environment. Exposure during leisure time includes exposure of (mainly young) people to pop music (e.g. concerts, night-clubs, portable CD-players and walk-mans), exposure during games and sports (shooting) and exposure of children to noisy toys. People may also be exposed to sound during recreation outdoors (nature areas, campsites, lakes, etc.).

This document will focus on the effects of exposure to transportation noise in the living environment, in offices and other otherwise quiet working environments and recreational areas. The effect of noise within factories is outside the scope of this project and is therefore not considered here. In chapter 4 exposure-effect relationships are given. Some of these relationships are well established, others are of a preliminary nature.

2 Acoustical aspects

Noise can be described by various noise metrics. The human hearing organ is not equally sensitive to sounds of different frequencies, therefore the sound pressure level (L) is 'A-weighted', and expressed as dB(A). Important noise metrics are:

- 1 $L_{Aeq,T}$: The equivalent sound level over a period of time: $L_{Aeq,T} = 10 \lg \left(\frac{1}{T} \int_0^T 10^{L(t)/10} dt \right)$.
- 2 L_{dn} : The day-night level. This metric is the equivalent sound level over a 24-hour period, with the sound levels during nighttime (22 – 7 h) increased by 10 dB(A).
- 3 L_{den} : The day-evening-night level. This metric is the equivalent sound level over a 24-hour period, with the sound levels increased by 5 dB(A) and 10 dB(A) during the evening (19 – 23 h) and during nighttime (23 – 7 h) respectively.
- 4 SEL: Sound Exposure Level. A metric used to describe single noise events. This metric can be described as the equivalent sound level during the event, normalized to a period of 1 second.

In this document L_{den} is chosen as the general noise metric for the 24 hour period, and $L_{Aeq, night}$ with usually a duration of 8 hours (23 – 07 h) is used for the nighttime exposure. L_{den} will most likely be selected as the standard metric by the European Union. SEL is used to describe the exposure to single noise events. Exposure-effect functions are presented using these metrics to describe the noise exposure.

Usually to evaluate an environmental noise situation, values of these noise metrics are assessed outdoors. Where appropriate, indoors noise levels can be assessed by taking into account the sound insulation of the dwelling.

For road traffic noise ISO 717-1:1996 specifies a noise spectrum given in the upper part of Table 1. If these relative octave band sound pressure levels are exponentially added, the result is 0 dB.

In the Netherlands for living rooms, large and small bedrooms the sound insulation is given at the lower part of the table (Reubsat, 1998). The sound insulation has been defined as the difference between the sound pressure level measured outside the dwelling at the facade (without reflections) and measured indoors.

Taking into account the ISO noise spectrum, the Netherlands sound insulation, and the A-weighting, the sound insulation for living rooms and large bedrooms is 28 dB(A), for smaller bedrooms 21 dB(A). In the Netherlands also the sound insulation of bedrooms for aircraft noise has been specified as 21 dB(A).

Table 1 Road traffic octave band spectrum (ISO 717-1:1996) (upper part of the table) and sound insulation in octave bands for the Netherlands situation (lower part of the table).

		Midfrequency octave band in hertz					
SPL per octave in dB	31	63	125	250	500	1000	2000
ISO spectrum		-18	-14	-10	-7	-4	-6
Sound insulation in dB for:							
Living room	17	22	23	22	26	29	29
Large bedroom	18	19	20	24	28	28	28
Smaller bedroom	26	14	21	22	23	21	21

3 Effects of noise exposure on health

3.1 Introduction

The effects of exposure to noise on health can be divided in the following groups:

- 1 hearing impairment;
- 2 stress related health effects (hypertension, cardiovascular diseases, effects on birth weight);
- 3 psychosocial effects (annoyance, effects on psychosocial well-being);
- 4 sleep disturbance;
- 5 effects on performance;
- 6 speech interference.

These effects have been examined in various epidemiological studies. In 1994, the Committee on Noise and Health, an international committee of the Health Council of the Netherlands (HCN), assessed the health effects of environmental and occupational noise exposure. Noise induced health effects with sufficient evidence for a causal relationship between exposure and effect as described by the Health Council of the Netherlands (1994) are: hearing loss, annoyance, hypertension, ischaemic heart disease, sleep disturbance and effects on cognitive performance of children in schools.

Table 2 gives an overview of the state-of-the-art of noise effects research. This table is based on Table 2 of the 1994 Health Council report, and has been updated since 1994 (see also Passchier-Vermeer and Passchier, 2000). Scientific evidence for different groups of effects has been rated in terms of “sufficient”, “limited”, “inadequate”, or “lacking”, respectively. Also an observation threshold has been defined, where sufficient scientific evidence was considered available. The observation threshold for an effect is defined as the lowest noise exposure level at which on average the effect was observed in epidemiological studies.

In the update recent reviews have been taken into consideration (Institute for Environment and Health, 1997; Morrell, et al., 1997; Shaw, 1996; Job, 1996; Carter and Job, 1998). Changes include the metric used to describe the noise exposure observation threshold for certain effects, such as hypertension and ischaemic heart disease. Secondly, the observation threshold for awakening by a single noise event has been lowered by 5 dB(A), and finally an observation threshold for sleep pattern changes and speech interference has been added.

Table 2 Long term and possible long term effects of exposure to noise and classification of the evidence for a causal relationship between noise and effect. The last three columns contain information on the observation threshold of an effect for which the causal relationship with noise exposure is judged to be 'sufficient'.

Effect	Classification of evidence ^a	Situation ^b	Observation threshold			Reference
			Metric	Value in dB(A)	Indoors/ Outdoors ^c	
Hearing impairment	Sufficient	Env	L _{Aeq,24h}	70 ¹	in	ISO, 1999
Hypertension	Sufficient	Env	L _{den} ^d	70 ²	out	HCN, 1994
Ischaemic heart disease	Sufficient	Env	L _{den}	70 ³	out	HCN, 1994
Biochemical effects	Limited	Env				
Immune effects	Limited	Env				
Birth weight	Limited	Env air				
Prenatal effects	Lack	Env				
Psychiatric disorders	Limited	Env air				
Annoyance	Sufficient	Env	L _{den}	42 ^{e,4}	out	Miedema and Oudshoorn, 2001
Psychosocial well-being	Limited	Env				
Performance	Sufficient	School	L _{Aeq,school}	70 ⁵	out	Passchier-Vermeer, 2000
Speech interference	Sufficient	Env, School	SEL	65 ⁶	in / out	Miedema and Passchier-Vermeer, 1999
Sleep disturbance, changes in:						
sleep pattern	Sufficient	Sleep				
awakening	Sufficient	Sleep	SEL	55 ⁷	in	HCN, 1997
sleep stages	Sufficient	Sleep	SEL	35 ⁸	in	HCN, 1994
subjective sleep quality	Sufficient	Sleep	L _{Aeq,night}	40 ⁹	out	HCN, 1997
heart rate	Sufficient	Sleep	SEL	40 ¹⁰	in	HCN, 1994
hormone levels	Limited	Sleep				
immune system	Inadequate	Sleep				
mood next day	Sufficient	Sleep	L _{Aeq,night}	>60 ¹¹	out	HCN, 1994
performance next day	Limited	Sleep				

a) Classification of evidence of causal relationship between noise and health.

b) Env = living environment, Sleep = sleep period time, School = exposure of children at school.

c) Value relates to indoor or outdoor noise assessment.

d) On average the differences between L_{den} and L_{dn} are only marginal. By analysis over 60 000 situations with road, railway or noise, the difference between L_{den} and L_{dn} appeared to be less than 0.5 dB(A). In specific situations however, the difference substantially larger.

e) The observation threshold is about 12 dB(A) lower for environmental impulse noise.

¹⁻¹¹ Exposure-effect relationships are given in Table 3 (if available).

3.2 Description of health effects

Health effects have been described by the Health Council of the Netherlands, Committee on noise and health (1994) and by Passchier-Vermeer and Passchier (2000), and will be briefly summarized here.

Hearing impairment

Hearing impairment is defined as an increase in the hearing threshold level. A hearing handicap is defined as the disadvantage imposed by hearing impairment sufficiently severe to affect one's personal efficiency in the activities of daily living. This disadvantage is usually expressed in terms of understanding conventional speech in low level ambient noise (International Standard; ISO, 1999).

Stress related health effects

Exposure to noise above a certain threshold can act as a stressor. Reactions to a stressor can be psychological, behavioural and somatic in nature. Cardiovascular effects such as ischaemic heart disease and hypertension belong in that third category. Ischaemic heart disease includes angina pectoris and myocardial infarction. Hypertension has been defined by the World Health Organization as a systolic blood pressure of at least 160 mmHg (this value corresponds to approximately 0.13 kPa), and/or a diastolic blood pressure of at least 95 mmHg.

Psychosocial effects

Psychosocial effects due to environmental noise that have been studied in epidemiological investigations include annoyance, psychosocial well-being, and psychiatric hospitalization.

The main psychosocial effect from exposure to occupational noise observed in epidemiological investigations is annoyance. Annoyance is a feeling of resentment, displeasure, discomfort, dissatisfaction, or offence when noise interferes with someone's thoughts, feelings or actual activities.

Annoyance in populations is evaluated using questionnaires. In this report exposure-effect relationships for noise annoyance are included as derived at TNO from a large international archive of noise annoyance studies (Miedema and Vos, 1998; Miedema and Oudshoorn, 2001). These relationships are described in a report (Miedema and Oudshoorn, 2001) which was prepared on behalf of the EU/DG Environment for the Working Group Dose/Effects which has the task to provide relationships between noise exposure and noise effects, for the preparation of an EU directive on environmental noise.

Annoyance questions in different international studies do not use the same number of response categories. This number varies from 3 to 11. In order to obtain comparable annoyance measures for all different studies, all sets of response categories have been translated into a scale ranging from 0 to 100, assuming that a set of annoyance categories divides the range from 0 to 100 in equally spaced intervals. In the definition of annoyance a cutoff point is chosen of 72 for the percentage highly annoyed (%HA), 50 for the percentage annoyed (%A) and 28 for the percentage (at least) a little annoyed (%LA).

Sleep disturbance

Sleep is a recovery process that is essential for humans to function properly. From the sleep EEG, two distinct phases of sleep can be distinguished: the NREM sleep and REM (rapid eye movement) sleep. NREM sleep covers four stages. Stages 1 and 2 are called light sleep, and stages

3 and 4 are called deep sleep (slow wave sleep: SWS). In stages 1 and 2 the transition to REM sleep or awakening occurs. In general, body- and brain restoration mainly occur during the SWS and the REM sleep respectively. During sleep, adults have sleep cycles of about 90 minutes, in which REM and NREM sleep occur alternating.

Adverse health effects are expected from chronic noise-induced interference with sleep, as it impairs the functions of sleep with respect to brain and body restoration (Horne, 1990; Carter, 1998). In addition to the physiological aspects of a noise-induced reduction of sleep quality, nighttime noise exposure of sufficient intensity is also related to subjectively experienced sleep quality (Passchier-Vermeer et al., 1998). Also, reduced sleep quality interferes with daytime functioning, adversely affecting mood next day and possibly cognitive performance of adults.

Sleep quality can be quantified by measures of subjective, behavioural, or physiological responses. To quantify subjective sleep quality sleep logs, diaries or questionnaires are used. The most commonly applied behavioural and physiological methods used to quantify sleep quality are EEG recordings, actimetry and pressing a button.

Effects on performance

There is sufficient evidence from laboratory experiments that the presence of noise can significantly impair cognitive performance. Noise can induce learned helplessness, increase arousal, alter the choice of task strategy, and decrease attention to the task. Noise may also affect social performance, mask speech and other sound signals, impair communication and distract attention from relevant social clues. Exposure of schoolchildren to noise can adversely affect their performing of cognitive tasks.

Speech interference

Noisy events, which increase the ambient noise level, may cause interference of conversation either by disturbance of the speaker (the speaker will have to speak louder) or by masking speech resulting in a reduced comfort of the listener and a decrease in sentences perceived.

4 Noise exposure-effect relationships – overview for the living environment

During a technical meeting on noise issues within the framework of UNITE a subset of health effects due to noise in the living, working environment and recreational areas was selected for further assessment. The selected environmental noise-induced effects are hypertension, ischaemic heart disease, annoyance, performance of school children, subjective sleep quality, speech interference, speech interference during working hours in offices and other otherwise quiet working environments and disturbance due to exposure to transportation noise during outdoors recreation in recreational areas. This report will focus on these selected issues, and their exposure-effect relationships (if available). In Table 3 exposure-effect relationships are listed.

Table 3 Exposure-effect relationships for exposure to various noise sources in the living environment. Preliminary (worst case) relationships for speech interference due to outdoors traffic noise in offices are also given. Exposure-effect relations listed for effects 1 to 6 are based on a 24 hours exposure, exposure-effect relations listed for effects 7-11 are based on exposure during the sleep period time only. Exposure-effect relationships relate to adult populations.

Effect	Exposure-effect relation	Reference
1 Hearing impairment	$\text{DHTL}_{T<10} = (u + v * \lg 10) (\lg (T + 1) / \lg 11) * (L - L_0)^2.$ $\text{DHTL}_{T>10} = (u + v * \lg T) * (L - L_0)^2.$ Where: DHTL: median hearing loss T: exposure time (years) u,v,L₀: constants dependent on the frequency of hearing impairment L: L_{Aeq, 8h} Note: These relationships are defined bij ISO (1999) for exposure to noise in the working environment. For environmental noise exposure, the constant L₀ is decreased by 5 dB(A) and taken over a 24 hours period	ISO, 1999
2 Hypertension	$\text{RR} = 0.5 + 0.007 * L_{\text{den}}$ for L_{den} > 70 dB(A) for road traffic and aircraft noise. No data for railway noise exposure is available (see text). Preliminary relationship where RR is the average relative risk.	
3 Ischaemic heart disease	$\text{RR} = 0.5 + 0.008 * L_{\text{den}}$ For L_{den} > 70 dB(A) for road traffic and aircraft noise. No data for railway noise exposure is available (see text). Preliminary relationship where RR is the average relative risk.	
4 Annoyance	Aircraft (little annoyed, annoyed, highly annoyed): $\%LA = -6.158 * 10^{-4} (L_{\text{den}} - 32)^3 + 3.410 * 10^{-2} (L_{\text{den}} - 32)^2 + 1.738 (L_{\text{den}} - 32);$ $\%A = 8.588 * 10^{-6} (L_{\text{den}} - 37)^3 + 1.777 * 10^{-2} (L_{\text{den}} - 37)^2 + 1.221 * (L_{\text{den}} - 37);$ $\%HA = -9.199 * 10^{-5} (L_{\text{den}} - 42)^3 + 3.932 * 10^{-2} (L_{\text{den}} - 42)^2 + 0.2939 (L_{\text{den}} - 42).$ Road traffic: $\%LA = -6.235 * 10^{-4} (L_{\text{den}} - 32)^3 + 5.509 * 10^{-2} (L_{\text{den}} - 32)^2 + 0.6693 (L_{\text{den}} - 32);$ $\%A = 1.795 * 10^{-4} (L_{\text{den}} - 37)^3 + 2.110 * 10^{-2} (L_{\text{den}} - 37)^2 + 0.5353 * (L_{\text{den}} - 37);$ $\%HA = 9.868 * 10^{-4} (L_{\text{den}} - 42)^3 - 1.436 * 10^{-2} (L_{\text{den}} - 42)^2 + 0.5118 (L_{\text{den}} - 42).$ Rail: $\%LA = -3.229 * 10^{-4} (L_{\text{den}} - 32)^3 + 4.871 * 10^{-2} (L_{\text{den}} - 32)^2 + 0.1673 (L_{\text{den}} - 32);$ $\%A = 4.538 * 10^{-4} (L_{\text{den}} - 37)^3 + 9.482 * 10^{-3} (L_{\text{den}} - 37)^2 + 0.2129 * (L_{\text{den}} - 37);$ $\%HA = 7.239 * 10^{-4} (L_{\text{den}} - 42)^3 - 7.851 * 10^{-3} (L_{\text{den}} - 42)^2 + 0.1695 (L_{\text{den}} - 42).$	Miedema and Oudshoorn, 2001
5 Performance	Unknown	
6 Speech interference	$f(\text{SEL}) = 0.05 (\text{SEL} - 65)$ for 65 dB(A) < SEL < 85 dB(A); $f(\text{SEL}) = 1$ for SEL > 85 dB(A); $f(\text{SEL}) = 0$ for SEL < 65 dB(A).	Miedema and Passchier-Vermeer, 1999
Where:		

		$f(\text{SEL})$: probability of speech interference in relation to SEL	
		<i>Worst case situation:</i> $N_{si} = 0.0016 * 10^{L/10} + 0.0117 * 10^{(L-15)/10} + 0.0040 * 10^{(L-25)/10}$ HCN, 1997 Where: L: $L_{Aeq,07-23h}$ (L assessed outdoors at the most exposed facade of the dwelling without reflections). N_{si}: Number of speech interruptions a year. <i>Worst case situation offices:</i> $N_{si} = 0.0007 * 10^{L/10}$ Where: N_{si}: Number of speech interruptions in offices due to environmental noise during a year (with 250 working days of 8 working hours) and with a probability of conversation equal to 0.10. L: $L_{Aeq,8h}$	
7	Awakening	$P_{w,n} = 0.18 \sum_i (\text{SEL}_{ind,i} - 55)$ Where: $P_{w,i}$: The average percentage of awakenings due to a noise event during sleep period time. $\text{SEL}_{ind,i}$: The SEL value determined in the bedroom for noise event i. <i>Worst case situation:</i> Number of awakenings a year = $0.096 * 10^{L/10}$ Where: L: $L_{Aeq,night}$ in the bedroom with night 8 hours, e.g. from 23.00 to 07.00 hours.	HCN, 1997
8	Sleep stages	Unknown	
9	Subjective sleep quality	Aircraft (highly sleep disturbance annoyed): $\%HS = 0.48 (L_{Aeq,23-07h} - 32.6) \text{ (preliminary relationship);}$ Road traffic: $\%HS = 0.62 (L_{Aeq,23-07h} - 43.2) \text{ (preliminary relationship);}$ Rail: $\%HS = 0.32 (L_{Aeq,23-07h} - 40.0) \text{ (preliminary relationship).}$ $L_{Aeq,23-07h}$ is assessed outside at the most exposed façade.	HCN, 1997
10	Heart rate	Unknown	
11	Mood next day	Unknown	

4.1 Hearing impairment

ISO 1999 gives a method to estimate noise-induced hearing impairment in populations exposed to continuous, intermittent or impulse noises during working hours. Exposure-effect relationships show that noise-induced hearing impairment predominantly occurs in the higher frequency range of 3000-6000 Hz, with largest effects observed at 4000 Hz. With increasing equivalent sound level and increasing exposure time, effects can also occur at lower frequencies (Passchier-Vermeer and Passchier, 2000). In Passchier-Vermeer (1993b) it has been argued that environmental noise exposure in the Netherlands will most likely cause no hearing impairment (HCN, 1994). Possibly, in megacities environmental noise exposure is so high that it may cause noise induced hearing impairment.

4.2 Stress related health effects

There are large individual differences in susceptibility. Also, people can intervene in their own situations, for instance by moving from noisy surroundings to quieter places. This may result in 'noise proof' populations exposed to the higher noise levels (TNO and RIVM, 1998). Notwithstanding these complications, conclusions on the relationship between noise exposure and cardiovascular disease appear possible from meta-analyses of the available epidemiological data on aircraft and road traffic noise. For railway noise no data is available (HCN, 1994). Taking into account that railway noise is less annoying and less sleep disturbing than road traffic noise, for railway noise the exposure-effect relationship may assumed to be shifted relative to road traffic noise by 5 dB(A) to higher noise levels.

A large number of laboratory experiments, reviewed by Passchier-Vermeer (1993a), have shown noise induced temporal changes in the cardiovascular system. Epidemiological environmental noise studies on changes in blood pressure and increased risk for ischaemic heart disease in adults are limited mainly to the effects of road traffic noise, with the exception of a Dutch study on the effects of aircraft noise (Knipschild, 1977). Several studies have observed that noise exposure can result in an increase in the percentage of people suffering from hypertension (As reviewed by Passchier-Vermeer and Passchier, 2000). Noise induced increase in occurrence of ischaemic heart disease and hypertension are described below.

a) *Ischaemic heart disease*

The relative risk of ischaemic heart disease for persons living in areas with road or traffic noise starts to increase at equivalent sound levels over 24 hours above 70 dB(A) measured at the facade outside the dwelling (HCN, 1994). Below this level, no noise-induced effect is to be expected (e.g. Babisch et al., 1998). Data in recent publications on cardiovascular effects from exposure to noise are not inconsistent with previous findings (e.g. Ising et al., 1997).

For the purpose of this project exposure-effect relationships have been derived for myocardial infarction. Possibly noise induced increase in number of hospital admissions for myocardial infarction is correlated with the increase in actual deaths as a result of this disease. The noise induced increase in number of deaths per year, may be estimated by:

$$n_{id} = (n_d / n_{ha}) * n_{iha}$$

Where:

n_{id} = noise induced increase in number of deaths (myocardial infarction) per year;

n_{ha} = total number of hospital admissions (myocardial infarction) per year;

n_d = total number of deaths (myocardial infarction) per year;

n_{iha} = noise induced increase in number of hospital admissions per year.

Estimates of occurrence of noise induced ischaemic heart disease (myocardial infarction) and hypertension in the Netherlands are given in Appendix I.

b) *Hypertension and blood pressure*

The relative risk of hypertension for adults living in areas with road or aircraft noise starts to increase at equivalent sound levels over 24 hours above 70 dB(A) measured at the facade outside the dwelling (HCN, 1994). Housing features such as double glazing and sound insulation, and personal habits (opening windows, moving to the quiet side of the house etc.) affect the actual noise exposure (HCN, 1994). It is unknown how these features affect the risk of hypertension.

There is also an effect of noise on blood pressure of children (Passchier-Vermeer, 2000). The effects of exposure to noise on systolic and diastolic blood pressure in children has been examined in several studies (Cohen et al., 1980; Regecova and Kelleroova, 1995; Evans et al., 1998; Hygge et al., 1996). These studies show a significant noise-induced increase in systolic and diastolic blood pressure in children. In some studies it cannot be excluded that social class has confounded the results (see also Lercher et al., 1998). In a German study (Evans et al., 1998; Hygge et al., 1996), schoolchildren were examined in the years Munich airport moved from one location to another. One location was situated close to the 'old' airport and the other close to the 'new' airport. The cross-sectional part of the study showed a marginally significant higher systolic blood pressure in children highly noise exposed at school. Children were matched on socio-economic characteristics. In the morning stress hormones were examined. Overnight resting levels of epinephrine and norepinephrine were significantly higher in the children exposed to aircraft noise at the old Munich airport in comparison to control groups. After the move of the airport levels of epinephrine and norepinephrine rose significantly among children living under the flight paths of the new airport.

4.3 Psychosocial effects

Environmental noise exposure significantly contributes to noise annoyance. Important effect-modifying factors are noise sensitivity, fear of the noise source, and a feeling that the noise could be avoided. These effect modifying factors have been identified in multivariate analyses of population data (Guski, 1999; Job, 1999; Miedema and Vos, 1999; Stallen, 1999). It is not possible to predict noise annoyance on an individual basis because of the large variety of (partly unknown) endogeneous and exogeneous characteristics that affect annoyance. However, relationships between noise annoyance and noise exposure have been established on a population level and the effects of several modifying factors have been quantified.

4.4 Sleep disturbance

Although in the 1990s several field studies were started or completed (Passchier-Vermeer et al., 1998; Fidell et al., 1998; Griefahn et al., 1996) there is still an urgent need for a tested model on the relationships between the adverse effects on sleep, and environmental night-time noise exposure, in which causal and modifying factors and their mutual relations are specified.

Subjective sleep quality

Preliminary relationships between self-reported sleep disturbance and nighttime (23.00 – 7.00 h) equivalent sound level measured at the most exposed facade outside of the dwelling have been derived from the same data archive of noise effect surveys as was used to specify annoyance relationships (HCN, 1997). In Table 2 preliminary relationships are given for the percentage of highly sleep-disturbance annoyed respondents (%HS). The percentage 'highly annoyed' is determined using a cut-off point at 72 on a scale from 0 ('not at all annoyed') to 100 ('very much annoyed'). These linear regression equations currently form the best estimate for quantification.

Awakening

Awakenings may be assessed by a number of different methods, including EEG recordings, subjects pressing a button after awakening, subjects reporting awakening the following morning and recordings of physical motility activity by actimeters. Relationships have been derived for noise and noise-induced awakenings. Awakenings are here defined as awakenings determined by EEG recordings. The relationship between the percentage of awakenings in an adult person and the SEL of an isolated noise event is given in Table 2. This (preliminary) relationship represents

the current level of knowledge; further investigation is necessary to obtain more definitive relationships (HCN, 1997).

In a worst case situation the number of noise-induced awakenings per year in a healthy person used to sleep in the specific situation is given by:

$$\text{Number of awakenings during a year} = 0.096 * 10^{L/10},$$

where: $L = L_{\text{Aeq,night}}$ with night 8 hours, e.g. from 23.00 to 07.00 hours. L is assessed in the bedroom. E.g., if $L = 30$ dB(A) the number of noise-induced awakenings is in the worst case situation equal to 96 times a year.

Awakening during sleeping time and subjectively experienced sleep quality are closely related (Passchier et al., 1998). To avoid that effects of nighttime noise are counted twice it is recommended that exposure-effect relationships for subjective sleep quality be used to describe effects on sleep.

4.5 Cognitive effects on school children

Some of the adverse effects of noise on children may be closely related to effects of noise on their caretakers. Studies show significant interruptions and lost teaching time in schools with high traffic noise levels. Most studies on the psychological effects of noise on children focussed on aspects of cognition (e.g. Cohen et al., 1980; Hygge et al., 1996; Haines et al., 1998). The best-documented noise effect is the effect on reading acquisition. There are fewer studies of noise effects on other aspects of cognitive processing, such as long term memory, attention, and motivation of children. Some studies have shown that children highly exposed to environmental noise for prolonged periods of time are less motivated when placed in situations where task performance is dependent on persistence. Further research into the mechanisms and contributing factors relating to noise exposure and adverse cognitive effects on children is needed to quantify effects.

4.6 Speech interference

Currently, exposure-effect relationships for speech interference in normal living conditions have not yet been extensively tested. However, on the basis of laboratory data, a preliminary best-estimate exposure-effect curve is given for 'vocal effort' at 1 m from the speaker and the required level of speech for adequate reception (Heusden et al., 1979; Plomp, 1986). At an ambient level of 55 dB(A) the speech level is just about sufficient to have an effect on the reception threshold. The speech reception threshold of a person is defined as the level of speech (dB(A)) at which the person is able to correctly reproduce 50% of the sentences can be heard by the receiver. It is assumed that the risk of speech interference increases linearly from 0 at an ambient level of 55 dB(A) to 1 at an ambient level of 75 dB(A) for an average population (Houtgast, personal communication). The relationship depends on specific circumstances, including individual variations in speech level, speech quality and willingness to raise speech loudness during higher ambient noise level periods.

It is important to note that these relationships are estimated for a speech level measured at 1 m from the speaker. In practice, the distance between speaker and listener will often be larger, resulting in reduced speech reception. In addition, the A-weighted level only gives an indication of speech interference; reliability of the use of this metric depends on the difference in sound spectrum of ambient noise and speech. Furthermore, in laboratory experiments constant ambient noise levels were used. In normal living circumstances ambient noise characteristics will be

different. Duration of the elevated background noise level also plays an important role, as people will behave differently depending on the duration of an intruding noise. During a short spell of noise, people will tend to stop speaking until the noise level drops. During longer periods of elevated noise levels, people will tend to stop their conversation completely, or change their location.

Relationships have been derived for speech interference and noise levels during isolated noise events (expressed in SEL) assuming an average duration of such events of 10 seconds (see also Miedema and Passchier-Vermeer, 1999), using the following tentative relationships for the probability of speech interruption during a noise event and SEL of the noise event:

$$\begin{aligned} f(\text{SEL}) &= 0.05(\text{SEL} - 65) && \text{if SEL is between 65 en 85 dB(A);} \\ f(\text{SEL}) &= 1 && \text{if SEL is larger than 85 dB(A);} \\ f(\text{SEL}) &= 0 && \text{if SEL is smaller than 65 dB(A).} \end{aligned}$$

Conversations usually only take place during a part of the time. Let z be the probability that a person is having a conversation. The probability of speech interruption is then:

$$\begin{aligned} f(\text{SEL}) &= 0.05z(\text{SEL} - 65) && \text{if SEL is between 65 en 85 dB(A);} \\ f(\text{SEL}) &= z && \text{if SEL is larger than 85 dB(A);} \\ f(\text{SEL}) &= 0 && \text{if SEL is smaller than 65 dB(A).} \end{aligned}$$

By a method similar to the one applied in the calculation of noise-induced awakenings, the number of speech interruptions in the *worst case situation* are calculated as a function of L . The calculations are more complicated, mainly because it has to be taken into account that people speak at various locations inside and outside the dwelling, with different shielding from outside noises. Let p_G be the probability of being indoors with windows closed and assume a sound insulation of 25 dB(A), let p_O be the probability of being indoors with windows partly opened and assume the sound insulation to be 15 dB(A), and assume that the rest of the time is spent outdoors (without sound insulation). The starting point is a person who is always at home. It is also assumed that conversation is independent of the location of the speaker and listener.

The maximal incidence of noise-induced speech interruptions is here assumed to be the sum of the expected maxima for each of three situations: outside, inside with closed windows and inside with partly opened windows. To be able to calculate the maximal incidence, values for z (probability of conversation), p_G (probability of being indoors with windows closed) and p_O (probability of being indoors with windows partly opened) have to be chosen. The probability of being outdoors, is $1 - (p_G + p_O)$. Assume that $z = 0.10$, $p_G = 0.75$ and $p_O = 0.22$ for the calculations in the following example. The probability of being outdoors between 06 and 22 hours is therefore equal to 0.03 (which is about half an hour a day). It is further assumed that speech only takes place during the day and evening, and not during the night.

Worst case situation:

$$N_{si} = 0.0016 * 10^{L/10} + 0.0117 * 10^{(L-15)/10} + 0.0040 * 10^{(L-25)/10}$$

(Miedema and Passchier-Vermeer, 1999).

Where:

$L = L_{Aeq,07-23h}$ assessed outdoors at the facade of the dwelling.

N_{si} = number of speech interruptions in a year.

It should be stressed that in situations with a specified L-value, but with another noise event pattern than the worst case situation, the number of speech interruptions is smaller and may even be zero.

For the purpose of this project the number of speech interruptions in offices due to environmental noise during a year (with 250 working days of 8 working hours) is estimated. For the worst case situation this number of speech interruptions is, with a probability of conversation equal to 0.10, equal to $0.0007 * 10^{L/10}$, with $L = L_{Aeq,8h}$ assessed outdoors at the facade of the office.

4.7 Annoyance in recreational areas

Under the National Park Overflight Act (1987) a series of investigations into the effects of aircraft passages to nature areas has been carried out in a number of areas in the United States. These investigations resulted in several reports, including Fidell, Silvati and Pearsons (1990); Fidell et al. (1992); Sneddon, Silvati, Pearsons and Fidell, (1991); Tabachnick, Fidell and Silvati, (1991); Tabachnick, Howe and Fidell, (1992); Anderson et al., (1993).

The report of Andersen et al., (1993) gives a number of exposure-effect curves (Figure 1 and Figure 2). However, it is uncertain whether exposure-effect curves derived for National Parks in the United States can be used to quantify effects in other areas, such as nature areas in Europe. No exposure-effect curves have yet been derived for recreational areas in Europe. Miedema (1995), Jong (1998), Gerretsen (1998), and Borst (1999) developed a method to evaluate noise exposure in recreational areas. This method has until now not been applied on such a scale that reliable exposure-effect relations could be established.

Figure 1 The percentage annoyed (A_{40}) as a function of the L_{Aeq} during a visit. At the left a worksheet is given that can be used to take into account the influence on annoyance of variables other than the L_{Aeq} . Firstly an adapted L_{Aeq} value is determined, subsequently a percentage annoyed can be read from the figure (source: Anderson et al., 1993).

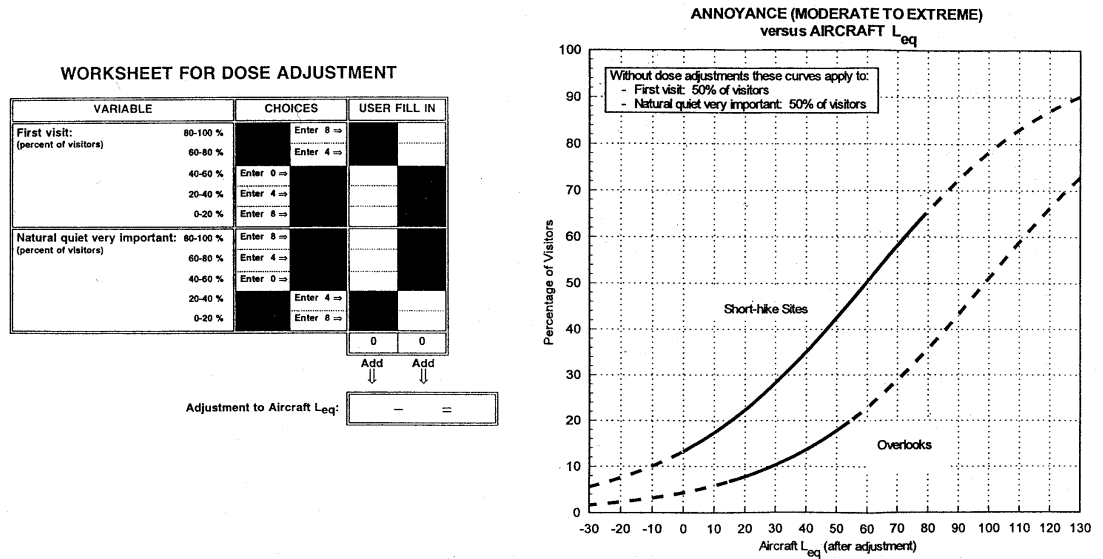
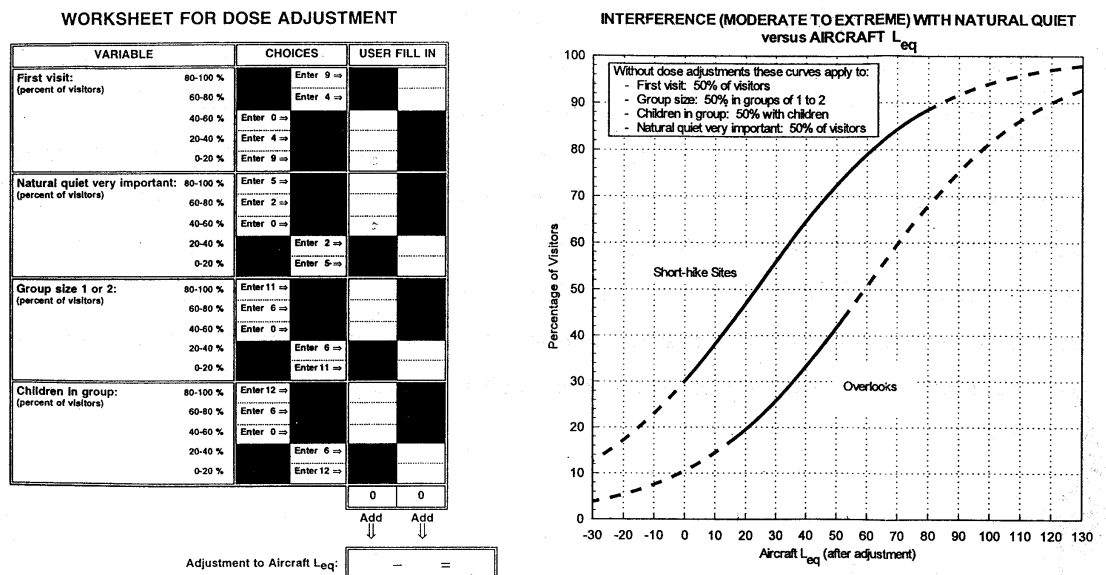


Figure 2 The percentage of visitors for which the natural quiet is being disturbed (NQ_{40}) as a function of L_{Aeq} during a visit. At the left a worksheet is given that can be used to take into account the influence on this disturbance of a number of variables other than the L_{Aeq} . Firstly an adapted L_{Aeq} value is determined, subsequently a percentage annoyed can be read from the figure (source: Anderson et al., 1993).



5 Conclusion

This report provides an overview of exposure-effect relationships for the effects of transportation noise on health in the living environment and preliminary relationships for speech interference from outdoors traffic noise in offices and other otherwise quiet working environments. Where exposure-effect relationships were not well documented, but current knowledge allowed a preliminary relationship, a best estimate has been given.

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A Appendix

Noise exposure in the Netherlands and it's effects.

The Health Council of the Netherlands (1994) has estimated the extent of occurrence of noise-induced health effects for the Netherlands (HCN, 1994). Estimates are subject to some uncertainty due to several factors, including the complexity of exposure-effect relations, inaccuracies in the data for the various noise exposures, intervening and confounding variables such as age, gender and stressors other than noise, combinations of exposures, effects of noise reducing measures etc. It must be noted that estimates are given for 1994, the present situation may be slightly different.

Demographic data used for the Netherlands used in the report are:

Number of inhabitants: about 15 million

Of these 25.8 % aged under 20 years and 74.2% (11.1 million) aged 20 years and over.

Number of dwellings: 5.8 million

Average number of inhabitants: 2.5 persons per dwelling

Table 4 describes the estimated number of people that are subject to noise-induced health effects in the Netherlands in 1993. The table is adapted from Table 3 of the Health Council of the Netherlands, Committee on Noise and Health (1994).

Table 4. Estimated number of persons in the Netherlands in 1993 with noise-induced health effects presented in order of magnitude classes and as percentages of the population. Numbers are given for the adult population of the Netherlands (persons aged 20 years and over).

Exposure situation and source	Effect	Class ^a	Percentage of population (%)
	hypertension	4	0.01 – 0.1
	ischaemic heart disease ^b	3	0.001-0.01
	noise-induced hearing loss	-	
	decreased sleep quality ^c	7?	> 10
road traffic	severe annoyance	7	> 10
civil air traffic	severe annoyance	6	1 – 10
military air traffic	severe annoyance	7	> 10 ^d
rail traffic	severe annoyance	6	1 – 10
industries	severe annoyance	6	1 – 10
combination of traffic	severe annoyance	6	1 – 10
other sources in the neighbourhood	severe annoyance	7	> 10

^a Classes are specified as:

- 1 none
- 2 < 100 persons
- 3 100 – 1000 persons
- 4 1000 – 10 000 persons
- 5 10 000 – 100 000 persons
- 6 100 000 – 1 000 000 persons
- 7 > 1 million persons

^b Number per year

^c Person at risk; the number of persons with effects could not be estimated.

Hypertension

The Health Council of the Netherlands has estimated the noise-induced increase in the number of hypertensive persons due to environmental noise sources at about 2300 (HCN, 1994). The increase in hypertensive persons due to aircraft noise from Schiphol-airport has been estimated at 1000 (Passchier-Vermeer et al., 1993). The total increase in number of hypertensive people in the Netherlands due to aircraft noise is estimated at 2500.

Ischaemic heart disease

It is estimated that the total increase in number of hospitalized patients suffering ischaemic heart disease, due to environmental noise exposure in the Netherlands is 330 (Health Council of the Netherlands, 1994; Passchier-Vermeer et al., 1993).

Noise induced hearing loss

Passchier-Vermeer (1993b) and Passchier-Vermeer et al. (1993), specify that in the Netherlands noise-induced hearing loss will most likely not result from environmental noise exposure.

Decreased sleep quality

Exposure levels during the night are largely unknown. Furthermore, observation thresholds and exposure-effect relationships for various aspects have not been established in a format that can be used to estimate the extent of the effects on the Dutch population. Therefore it is difficult to precisely estimate the effects of noise exposure on the sleep within the Dutch population. However, for subjectively experienced sleep quality an observation threshold has been given, allowing an estimate of the number of persons affected. The number of people at risk is estimated to be over 1 million, of which 150 000 due to industrial noise, at least 600 000 due to road traffic noise, at least 30 000 due to railway noise and an unspecified number due to air-traffic noise.

Annoyance

In the last decades, there has been an extensive increase in annoyance due to environmental noise sources in the Netherlands. The situation in the Netherlands appears to have worsened since 1975, despite the Noise Nuisance Act coming into force in the beginning of this period. Since 1987 however, the situation has again improved somewhat for most noise-sources (De Jong et al., 2000). In some situations, people are annoyed by more than one noise source. The prevalent combination of noise sources is that of road and air traffic. It is estimated that 16% and 8% of the Dutch population is annoyed and severely annoyed respectively, by a combination of these sources. Noise caused by activities in the neighbourhood nowadays is the main source of annoyance. Various sources of neighbour-noise appear to add up to 66% of the people annoyed, of which 26% severely.