TNO Inro

Nederlandse Organisatie voor
toegepast-natuurwetenschappelijk
onderzoek / Netherlands Organisation
for Applied Scientific Research

Schoemakerstraat 97
P.O. Box 6041
2600 JA Delft
Nederland

www.tno.nl

T +31 15 269 68 29
F +31 15 262 43 41
inro@inro.tno.nl

TNO Inro report 2002-59

Elements for a position paper on night-time transportation noise and sleep disturbance

Date	January 2003
Authors	H.M.E. Miedema W. Passchier-Vermeer H. Vos
City	Delft
Number	02 5N 160 61241
ISBN-number	90-6743-981-9

TABLE OF CONTENTS

1 INTRODUCTION 3
2 CONCEPTUAL FRAMEWORK 5
3 NOISE METRICS AND SLEEP DISTURBANCE MEASURES 9
3.1 Noise metrics 9
3.2 Sleep disturbance measures 10
3.2.1 Self-reported sleep disturbance 11
3.2.2 Physiological and motility variables 12
3.3 Relationship between L_{night} and instantaneous effects 15
4 RELATIONSHIPS BETWEEN NIGHT-TIME NOISE AND MOTILITY 17
4.1 Measurement and meaning of motility 17
4.2 Information regarding exposure-effect relationships 18
4.3 Relationships between SEL* or L_{max}* and instantaneous motility. 23
4.4 Relationships between L_{night} and long-term motility 26
4.5 Comparison with results of other field studies 27
5 RELATIONSHIPS BETWEEN NIGHT-TIME NOISE AND SELF-REPORTED SLEEP DISTURBANCE 33
5.1 Introduction 33
5.2 Exposure-effect model 33
5.3 Data 34
5.4 Relationships between exposure at the most exposed façade and self-reported sleep disturbance 38
5.5 Influence of difference in exposure between the most exposed and the bedroom façade 42
5.6 Influence of insulation of the bedroom 44
5.7 Influence of exposure to an additional source 47
5.8 Influence of daytime noise 48
6 CONCLUSION AND DISCUSSION 49
7 REFERENCES 53
APPENDIX 61

1 INTRODUCTION

The EU Directive on the Assessment and Management of Environmental Noise (END) specifies L_{night} as the indicator for sleep disturbance. This report presents relationships between L_{night} and sleep disturbance for transportation noise. These relationships can be used in a position paper on relationships between L_{night} and sleep disturbance for transportation noise by the working group "Health and socio-economic aspects". The working group intends to provide such a position paper to the Noise Committee (under the procedure laid down in article 13 of END) as a basis for the revision of Annex III of END.

The main objective of this report is to supply relationships between noise-induced *sleep disturbance* and *night-time noise exposure* expressed in terms of L_{night}, for aircraft, road traffic and railway noise.
The following points, related to the main objective, will be addressed in the report:

- The night-time noise exposure metric has already been determined in the Directive: L_{night}. A measure for sleep disturbance has not yet been selected. Therefore, measures that can be used for quantifying sleep disturbance in the population in the context of END will be proposed;
- In addition to curves for sleep disturbance as a function of L_{night}, the 95%- confidence intervals around these curves will be established in order to quantify the (un)certainty associated with the curves;
- Outdoor night-time noise exposure at the most exposed facade of a dwelling (L_{night}) is not the only acoustical factor that influences sleep disturbance. Therefore attention will be given to the role of other factors, notably the actual noise exposure at the façade of the bedroom, and the difference between outdoor and indoor noise levels (sound insulation) of bedrooms.

Helpful input for the underlying work and/or comments on a draft of the report has been given, among others, by the above mentioned working group “Health and socio-economic aspects [1], dr Alain Muzet from CNRS in France, and dr Bernard Berry from Bel Acoustics in the United Kingdom.

---

[1] The members of the working group “Health and socio-economic aspects”are:
Martin van den Berg (chairman), Ministry of Environment, Netherlands
Tom Worsley (co-chairman), DTLR, United Kingdom
Sirkka-Liisa Paikkala, Ministry of Environment, Finland
Werner Talasch, Magistrat der Stadt Wien, Austria
Tor Kihlman, Chalmers University of Technology, Sweden
Jose Palma, (NGO-Quercus), Universidade de Lisboa, Portugal
Anne Ohm, Cowi A/S, Denmark
Gilles Paque, European Commission, Belgium
Matti Vainio, European Commission, Belgium
Jacques Lambert, Inrets, France
Birgitta Berglund, University of Stockholm, Sweden
Isabel López Barrio, Instituto de Acústica, Spain
Rainer Guski, Ruhr-Universität Bochum, Germany
Gaetano Licitra, Arpat Dipartimento provinciale di Pisa, Italy
Roger Strube, Deutsche Bahn AG, Germany

2 CONCEPTUAL FRAMEWORK

No widely accepted models are available that describe the mechanisms through which noise induces effects on people. Four routes have been distinguished through which noise exerts its influence. A route is characterised by the state or process that is influenced by noise. Roughly, noise can influence sound (such as speech) perception (through masking), attention, arousal, or the affective/emotional state (Miedema, 2001). These routes are (partially) independent in the following sense: noise can induce an effect through one of the routes without having an effect through another route. For example, noise can have an effect on attention without the occurrence of masking, arousal, or an affective/emotional response. The arousal route is the most relevant route with respect to sleep disturbance.

A conceptual framework for studying noise-induced sleep disturbance is presented in figure 2.1 (cf. Ising et al., 1999). This framework gives a rough outline of steps in the development of effects. The framework in figure 2.1 suggests the sequential occurrence of the immediate processing of noise, instantaneous arousal/stress reactions and changes in one night and the day after, chronic (possibly reversible) changes, and an increased risk of (irreversible) health effects. This process is initiated by noise exposure during the sleep period, and depends on the state and characteristics of the individual. Furthermore, there is feedback concerning the occurrence of acute and chronic effects that influences the occurrence of further (stress-related) effects. The framework does not imply that instantaneous effects necessarily contribute to chronic changes or long-term health effects, or that chronic changes necessarily contribute to long-term health effects. Recovery mechanisms can restore balances and prevent the occurrence of further effects.

Arousal is an important step in the causal chain from noise exposure in the sleep period to chronic changes and long-term health effects. Arousal may occur when a person is asleep, but also when he is awake. Arousal has been viewed as a single dimensional phenomenon that was mediated by the ascending reticular activation system (ARAS). However, this has been questioned, and the present view is that the arousal system is fractionated into many different subsystems. Low arousal can be counteracted by noise and in that way noise can prevent long response times (Corcoran, 1962) and lapses in attention (Smith et al., 1998) when performing a task. This effect of noise has been demonstrated to involve changes in the central adrenaline level (Smith et al., 1998, Smith, 1998). The higher the arousal is, the lower the probability of falling asleep or continuing sleep. Because of its arousing potential and because sound is still being processed during sleep, sound can prevent a person from falling asleep or awake a person. The instantaneous arousal reaction of sleeping persons to sound often is more subtle than awakening and may involve change from a deeper to a lighter sleep stage, temporary increase in heart rate and systolic blood pressure, release of stress hormones in blood, and small temporary movements of the body and extremities. Since sleep is necessary for restoration of presumably all bodily systems, chronic changes and adverse health effects may be expected from chronic noise-induced arousal reactions during sleep.

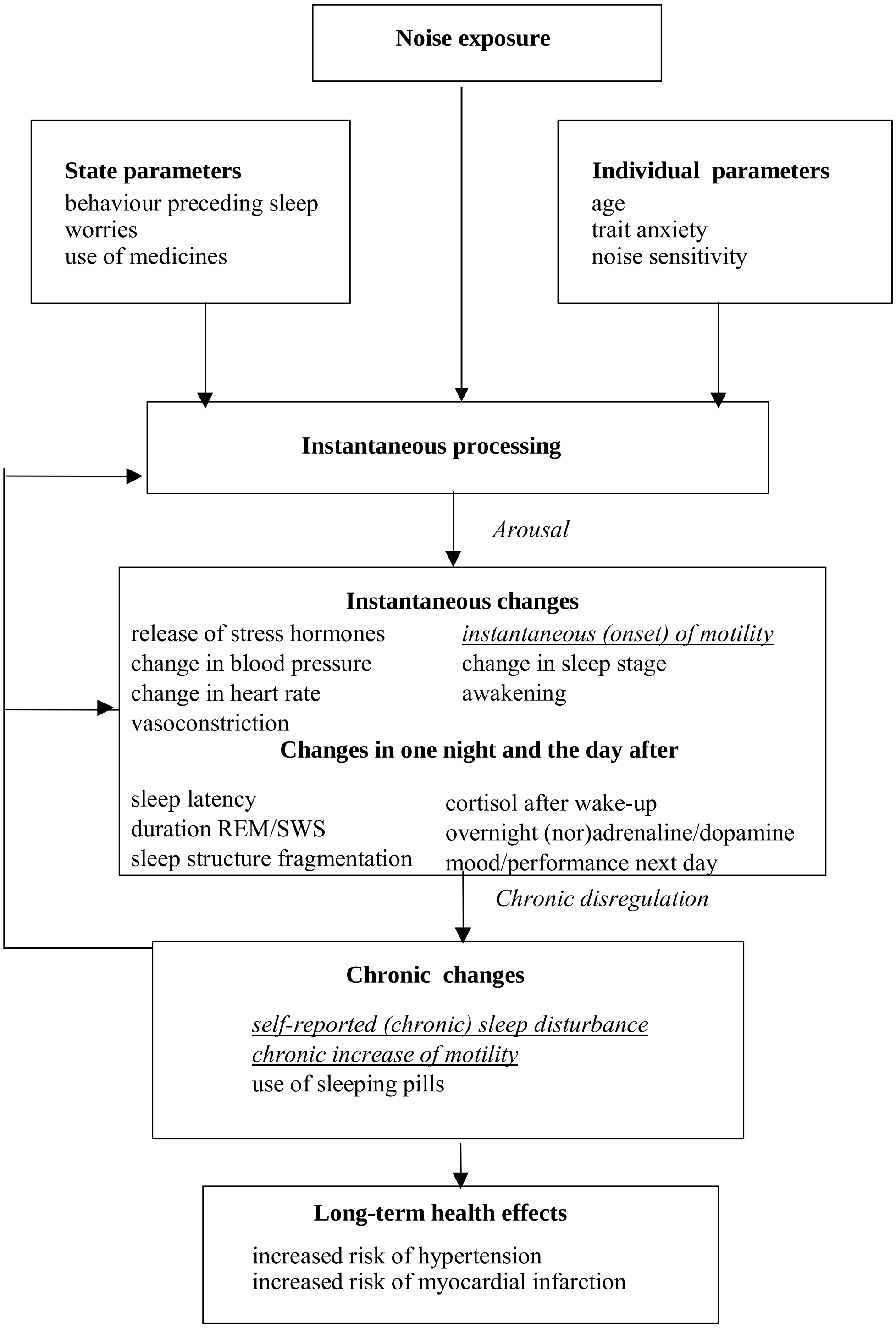

Figure 2.1: Framework for the study of noise-induced sleep disturbance. The effects mentioned are examples and not necessarily proven effects of noise on sleep. This report provides relationships between night-time noise exposure and the underlined effect variables.

A comprehensive assessment of the effects of noise on sleep considers all three effect stages in figure 2.1 (instantaneous changes and changes in one night and the day after, chronic changes, long-term health effects). This report focuses on the effects from figure 2.1 for which there is a sufficient basis to establish (provisional) relationships. It provides relationships between night-time noise exposure, and the instantaneous effects (onset of) motility, and the chronic effects increase of mean motility during sleep and self-reported sleep disturbance. At present there is not a sufficient basis for establishing relationships between night-time noise and long-term health effects. Chapter 3 describes the noise metrics involved in the relationships, and the selection of sleep variables. Relationships are presented in the chapters 4 and 5.

3 NOISE METRICS AND SLEEP DISTURBANCE MEASURES

3.1 Noise metrics

L_{night} can be used as a predictor of *chronic effects* of exposure to night-time noise, such as self-reported sleep disturbance. Because it integrates the contributions of individual noise events to the overall night-time exposure, it is also related to the long-term incidence of instantaneous effects. L_{night} is the “average” night-time noise level. It is one of the three components of L_{den}, the day-evening-night level. L_{den} and L_{night} do not include reflections of the façade for which they are assessed so that they describe the incident sound at the façade. L_{night} is defined as the A-weighted “average” sound level, L_{Aeq} (see: ISO 1996-2 (2002)), over a year for the period 23 – 7h at the façade of a dwelling with the highest L_{den}. Noise measurements or calculations with a view to noise annoyance are conducted for this façade, so that it is most simple in practice to also assess the night-time exposure for this façade. The façade with the highest L_{den} is called the most exposed façade.

Instantaneous effects of noise on sleep, such as awakenings or instantaneous motility, are related to descriptors of individual noise events such as the maximal sound level (L_{max}) or the sound exposure level (*SEL*; see: ISO 1996-1:2002). According to its basic definition, the assessment of *SEL* requires the integration of the sound energy related to a single event, including low levels that may occur at the beginning and the end of the event. However, due to the presence of background noise, the assessment of these low levels often is not practically feasible. Therefore, often low levels are not included, and *SEL* is taken to be the total sound energy in the period in which the level of the event is above L_{max} -10 (or L_{max} minus another value). Sometimes this quantity is denoted by *SEL10* to expressed the use of a lower boundary, but more often it is also denoted by *SEL*. For transportation sources there may exist differences between *SEL* and *SEL10* of several decibels. Because publications often are not clear about the use of a lower boundary, we use *SEL* while there may or may not have been used such a lower boundary, except in the derivation of final exposure-response relationships involving *SEL* in section 4.6. The data used for that derivation enabled us to be explicit about this point. When the night-time noise is caused by separate events (e.g., passages of aircraft, motor vehicles, or trains), L_{night} is the “sum” of the individual sound exposure levels caused by these events “divided” by the duration of the night:

$$L_{night} = 10\lg(\Sigma_i 10^{SELi/10} / 10512000),$$

where 10512000 is the number of seconds in a year in the night period 23 – 7h. This can also be written as:

$$L_{night} = 10\lg \Sigma_i 10^{SELi/10} - 70.2.$$

If all *N* events have equal *SEL*, then this equation can be simplified as follows:

$$L_{night} = SEL + 10\lg N - 70.2.$$

Thus, by the definitions of these metrics, there is a clear relation between L_{night} and the *SEL* of individual events. For example, using the above equation, it can be calculated how many events with a given equal *SEL* together cause a year-time L_{night} = 45 dB(A) (see table 3.1). With *SEL* = 90 dB(A) 332 events in a year cause L_{night} = 45 dB(A). As a consequence of this relation between L_{night} and *SEL* of individual events, a limit with respect to L_{night} also imposes limits on the number and levels of events. This is further discussed in the last section of this chapter.

Table 3.1: Number of events with given *SEL* that together cause a year-time L_{night} = 45 dB(A).

SEL (in dB(A))	*N* (number of events)
75	10512
80	3324
85	1051
90	332
95	105
100	33
105	11
110	3
115	1

While *SEL* is a measure of the total sound energy of an event, L_{max} describes the top of the event (integrated over 125 (‘F’) or 1000 (‘S’) ms). In practice, L_{max} is easier to measure than *SEL*, and in human effects studies it is often used as a descriptor of single noise events. Therefore it is important that there are relations between L_{max} and *SEL*. These relations depend on the time pattern of the noise event. Rules that translate *SEL* into L_{max}, and vice versa, are discussed in the last section of this chapter. The fact that rules exist which give a reasonably accurate description of the correspondence between L_{max} and *SEL*, means that L_{night} not only imposes limits on *SEL* (and number) of noise events, but also on L_{max} (and number) of events.

In this report, noise metrics for the indoor exposure (i.e., in the bedroom) will have an *, while for the general use or for the outdoor exposure no * will be added. Thus, L_{night} and *SEL* are the metrics in general or for outdoor exposure, depending on the context, while L_{night}* and *SEL** are metrics of the indoor exposure. Furthermore, *LDiff1* is L_{night} at the most exposed façade minus the similar L_{Aeq} at the façade of the bedroom, and *LDiff2* is outdoors L_{Aeq} at the façade of the bedroom minus L_{Aeq} in the bedroom for sleeping period. When the sleeping period is assumed to be 23 – 7h, then *LDiff2* is night-time L_{Aeq} at the façade of the bedroom minus L_{night}*. Consequently, then L_{night}* = L_{night} - *LDiff1* - *LDiff2*.

3.2 Sleep disturbance measures

Sleep disturbance can be described with physiological and motility measures, and on the basis of self-reported observations or evaluations. In this section self-reported sleep disturbance measures, and (non-invasive) physiological and motility measures are described.

3.2.1 *Self-reported sleep disturbance*

Self-reported sleep disturbance is investigated by means of a questionnaire with questions regarding sleep disturbance. Often sleep disturbance is not the main focus of the questionnaires used in studies of self-reported noise effects. Sleep disturbance questions in different studies may use different numbers of response categories. In order to obtain disturbance measures for different studies that are comparable, all sets of response categories are translated into a scale from 0 to 100. The translation is based on the assumption that a set of sleep disturbance categories divides the range from 0 to 100 in equally spaced intervals. Then the lower boundary of the lowest category is equal to 0 and the higher boundary of the highest category is 100. The general rule that gives the position of an inner category boundary on the scale from 0 to 100 is: $\text{score}_{\text{boundary } i} = 100i/m$ (see table 3.2). Here i is the rank number of the category boundary, starting with 1 for the upper boundary of the lowest sleep disturbance category, and m is the number of categories.

The distribution of the sleep disturbance scores of a population at a given L_{night} can be summarised in various ways. Often a cut-off point is chosen on the scale from 0 to 100 and the percentage of the responses exceeding the cut-off is reported. If the cut-off is 72 on a scale from 0 to 100, then the result is called in this report the percentage ‘highly sleep disturbed’ persons (*%HSD*), with a cut-off at 50 it is called the percentage ‘sleep disturbed’ (*%SD*), and with a cut-off at 28 the percentage ‘(at least) a little sleep disturbed’ (*%LSD*). These definitions are analogous to the definitions of the percentage highly annoyed persons (*%HA*), the percentage annoyed persons (*%A*), and the percentage ‘(at least) a little annoyed persons’ (*%LA*). An alternative to these types of measures is the average sleep disturbance score.

Relations between night-time noise exposure and self-reported sleep disturbance will be presented in chapter 5.

Table 3.2: Boundary quantifications on a 0 - 100 scale for different sleep disturbance scales.

Number of effective categories	Boundary quantifications
2	0-50-100
3	0-33-67-100
4	0-25-50-75-100
5	0-20-40-60-80-100
6	0-17-33-50-67-83-100
7	0-14-28-43-57-72-86-100
10	0-10-20-..-80-90-100
11	0-9-18-..-82-91-100

3.2.2 Physiological and motility variables

Important measures of sleep are EEG measures (number and duration of awakenings, sleep latency time, changes in the pattern of sleep stages), changes in vegetative autonomic functions (heart rate, blood pressure, vasoconstriction and respiratory rate), and motility measures (Passchier-Vermeer, 1993). This section discusses the measurement of these variables, the availability of information regarding exposure-response relationships, and the selection of variables for the assessment of exposure – response relationships in this report.

The *sleep polygraph* continuously records electroencephalograph (EEG) activity, eye movement (EOG) and muscle tone (EMG). These data are used to classify sleep into various stages, and to assess time of falling asleep and wake-up time. Also sleep variables such as total sleep time and total time spent in Slow Wave Sleep (SWS, stages of deep(er) sleep) and in the stage of Rapid Eye Movement (REM, also called dream sleep) can be assessed on the basis of sleep polygraph recordings. Polygraphic indicators of responses to individual noise events are changes from a deeper to a less deep sleep, and EEG-awakening.

Electrocardiography (ECG) continuously records heart rate and measures of blood pressure, and *plethysmography* (during sleep the recording device is usually worn around a finger) continuously measures heart rate and relative blood pressure. For sleeping persons mean heart rate, mean systolic and diastolic blood pressure, and variability in heart rate are usually assessed. Indicators of responses to individual noise events are instantaneous changes in (variability of) heart rate and changes in systolic blood pressure.

Collecting assays of overnight *urinary catecholamines* is a method to study sympathetic nervous activity. The assays represent the total of catecholamines released during sleep period time, not taken up by sympathetic nerve endings. The method does not allow the detection of peak levels of circulating catecholamines, such as may occur in response to noise events during sleep. Overnight and 24 hours *cortisol levels* may be important indicators of risk of chronic cardiovascular disorders. Sampling of cortisol required blood sampling, but recently a method of assessing cortisol levels in fluvia has been developed, which may provide an adequate non-invasive method of sampling cortisol levels in large groups of people.

Motility is the term used for accelerations of the body or body parts during movements. It is measured with actimeters, usually worn on the wrist in field research. Motility measures of total sleep time, time of falling asleep and wake-up time have been validated with sleep polygraph measures as standard. Measures of instanteneous motility are the probability of motility and the probability of onset of motility in a fixed time interval, e.g. a 15-s, 30-s or 60-s interval. Measures of instanteneous noise-induced motility are the increase in the probability of motility, and the increase in the probability of onset of motility. The noise–induced increase in probability of (onset of) motility is the difference between the probability during noise events minus the probability in the absence of noise. Actimetry has been used in the last decade to monitor sleep disturbance in large field studies with subjects sleeping at home exposed to the usual aircraft, road traffic or railway noise (Ollerhead et al., 1992; Horne et al., 1994; Fidell et al., 1996, 1998; Griefahn et al., 1999; Passchier-Vermeer et al., 2002). In these studies, also the night-time noise exposure has been assessed and related to motility measures.

Table 3.3 indicates for the physiological and motility variables whether a relationship with night-time noise exposure has been found. This is an important criterion for the selection of effect variables for which relations with noise metrics are presented. A further criterion is that exposure-response relationships have been based on extensive field studies. The selection of effect variables from each of the three effect categories distinguished in chapter 2 is discussed below. Because of its apparently simple meaning and the attention it has got in the past, awakening is discussed extensively.

In the category *instantaneous effects and effects in the night and day after* (see first part of table 3.3), awakening can be assessed by polysomnography and by behavioural indication of awakening (usually the pressing of a button). By comparing the time of awakening with the time of a noise event, noise-induced awakening and the probability of noise-induced awakening can be assessed. (Onset of) motility and awakening found on the basis of EEG recordings are higly correlated. In the UK sleep disturbance study, Ollerhead et al. (1992) found for their study population that during sleep there is on average an EEG-awakening in 40% of the 30-s intervals with onset of motility. Unfortunately, it is unknown whether this 40% is also valid for noise-induced awakenings. In 12% of the 30-s intervals with an EEG-awakening motility does not occur.

The results of several field studies with subjects exposed to night-time aircraft noise have been combined to estimate the average number of intervals with onset of motility, the average number of EEG-awakenings, and the average number of behavioural awakenings (Ollerhead et al., 1992; Fidell et al., 1995a, 1995b, 1998; Passchier-Vermeer et al., 2002). For the populations studied it is estimated that during a sleep period there are on average 42.8 intervals with onset of motility, 17.1 EEG-awakenings, and 1.56 behavioural awakenings. This implies that for the subjects considered on average one behavioural awakening corresponds to 11 EEG-awakenings and 27 intervals with onset of motility (Passchier-Vermeer, 2003, draft). A rough estimate for periods without night-time noise is that one behavioural awakening corresponds to 12 EEG-awakenings and 30 intervals with onset of motility (Passchier-Vermeer, 2003, draft).

On the basis of meta-analyses, several (groups of) researchers (Pearsons et al, 1989; FICON, 1992; Passchier-Vermeer, 1994; Finegold et al., 1994; Bullen et al., 1996; Fidell, 1998; Finegold and Elias, 2002) have proposed exposure-effect relationships that give the probability of noise-induced awakening as a function of the noise event descriptors L_{max}* and *SEL**. The early review by Pearsons et al. (1989) showed that exposure-effect relationships derived from laboratory and (a few) field studies are very different. At the same L_{max}* or *SEL**, stronger effects have been observed in laboratory studies compared to field investigations. These differences have been explained by habituation to night-time noise of subjects in field studies in contrast to the unusual exposure of subjects in laboratory studies (Pearsons et al., 1989). Some of the later meta-analyses have taken this observation into account, while others did not (FICON, 1992; Finegold et al., 1994).

The most recent synthesis curve of awakening as a function of *SEL** (Finegold and Elias, 2002) has been based on eight field studies (Fidell et al., 1995a, 1995b, 1998; Pearsons et al., 1973; Öhrström et al., 1988; Vernet, 1979; Vallet et al., 1980; Ollerhead et al., 1992). From these eight studies Fidell et al. (1998) derived 100 data points, through which Finegold and Elias (2002) fitted a curve. Finegold and Elias (2002) claim that the eight studies measured behavioural awakenings, but in fact in several studies EEG measurements and actimetry has been performed (Vernet, 1979; Vallet et al., 1980; Öhrström et al., 1988; Ollerhead et al., 1992) and results have been 'translated' to behavioural awakenings by applying the 40%-rule for conversion of motility to EEG-awakenings and by assuming that an EEG-awakening is identical to a behavioural awakening. Unfortunately, the validity of the 40 % rule for noise-induced awakening has not been verified and the assumption that EEG-awakenings are identical to behavioural awakenings is incorrect. Moreover, the datapoints are based on different numbers of observation, but have not been assigned a different weight when fitting a curve through them. For these reasons, the curve presented by Finegold and Elias (2002) is considered to be not sufficiently accurate for application in practice (see Passchier-Vermeer, 2003, draft, for a more detailed discussion).

Table 3.3: Physiological and motility variables measured in relation to sleep. An overview is given of the measurement methods used, the observed associations with other sleep variables, and exposure metrics with which relations have been reported.

INSTANTANEOUS EFFECTS				
Variable	**Measurement method**	**Association with other variables**	**Relations with exposure metric(s)**	**Selected references**
Instantaneous (onset of) motility	Actimetry	EEG- and behavioural awakening	SEL, L_{max}	Ollerhead, 1992; Horne, 1994; Fidell, 1995, 1998, 2000; Griefahn, 1999; Passchier, 2002
EEG-awakening	Polygraphy (EEG, EMG, EOG)	Instanteneous (onset of) motility and behavioural awakenings	SEL, L_{max}	Pearsons[*], 1989; Ollerhead, 1992; Horne, 1994
Behavioural awakening	Pressing a button	Instanteneous (onset of) motility and EEG-awakenings*	SEL, L_{max}	Fidell, 1995,1998,2000; Finegold and Elias, 2002; Passchier, 2002
Instantaneous increase and variability of heart rate, cardiac arrhythmia	ECG, plethysmography		-	Carter, 1994, 1995; Muzet, 1978; Vallet, 1983; Di Nisi, 1990; Kumar, 1983; Hofman, 1987; Jurriens, 1983; Wilkinson, 1984; Griefahn, 1989; Öhrström, 1988; Bonnet, 1997; Whitehead, 1998
Instantaneous vasoconstriction, change in blood pressure	ECG, plethysmography		-	Guilleminault, 1995; Okada, 1994; Carter, 1998

- References included in the Pearsons overview have not been cited here;

EFFECT IN ONE NIGHT AND THE DAY AFTER				
Variable	**Measurement method**	**Association with other variables**	**Relations with exposure metric(s)**	**Selected references**
Sleep latency time before a sleep period (SLT)[*]	Polygraphy (EEG, EMG, EOG), actimetry	Self-reported sleep quality in the morning	$L_{Aeq}(SLT)$	Thiessen, 1983; Öhrström, 1998; Passchier, 2002
Mean motility during a sleep period (SPT)	Actimetry	Self-reported sleep quality in the morning	$L_{Aeq}(SPT)$	Öhrström, 1988, 1998; Passchier, 2002
Duration SWS during a sleep period	Polygraphy (EEG, EMG, EOG)	-	-	Thiessen, 1983; Carter, 1995
Duration REM during a sleep period	Polygraphy (EEG, EMG, EOG)	-	-	Jurriëns, 1983
Sleep structure, fragmentation during a sleep period	Polygraphy (EEG, EMG, EOG), actimetry	-	-	Thiessen, 1983; Carter, 1995; Jurriëns, 1983 Passchier, 2002
Cortisol level after wake up	Blood sample		-	Ising, 1983; Maschke, 1997a, 2002; Born, 1986
Adrenaline, noradrenaline and dopamine levels overnight	Urine sample		-	Maschke, 1995 a, 1995b; Carter, 1994, 1998; Harder, 1999

* Only the end of sleep latency time (time of falling asleep) can be assessed by measurement. Start of sleep latency involves the evaluation of the subject.

CHRONIC EFFECT				
Variable	**Measurement method**	**Association with other variables**	**Relations with exposure metric(s)**	**Selected references**
Mean motility during sleep	Actimetry	Number of - health complaints; - awakenings; - sleep complaints; - adverse sleep effects; Self-reported sleep quality	L_{night}	Passchier, 2002

Several field studies have been conducted regarding noise–induced *instantaneous motility*. For this effect, relationships have been established with *SEL* or L_{max}, for aircraft noise only. Increased instantaneous motility during sleep is considered to be a sensitive behavioural marker of arousal, but the relation with arousal is not simple. Also other factors, such as the need to relieve the pressure on body parts for better blood circulation, cause motility. Thus, only a fraction of the motility marks arousal. Instantaneous motility has been related to instantaneous changes in the EEG-pattern that reflect awakening (see table 3.3, in the column 'Association with other variables'). Relations of instantaneous motility with *SEL* or L_{max} will be presented in section 4.3.
In the category *chronic changes* (see second part of table 3.3), only for mean motility during sleep there is sufficient data to establish exposure-effect relationships, for aircraft noise. Change in mean motility during sleep is considered to be a sensitive indicator of chronic changes with health implications (see table 3.3, in the column 'Association with other variables'). Relations for mean motility will be presented in section 4.4.
Although it is plausible on the basis of mechanistic considerations that night-time noise induces *long-term health effects* (see third part of table 3.3), only recently the first evidence for such relations has been published (Maschke et al., 2002). Currently, there is not a sufficient basis for establishing exposure-effect relationships for the category of long-term health effects.

Thus, relationships with noise metrics are presented for the following motility variables: instantaneous motility (sections 4.3) and mean motility (section 4.4). These relationships are presented in addition to the relationships for self-reported sleep disturbance (section 5.4).

3.3 Relationship between L_{night}* and instantaneous effects

A long-term measure of an instantaneous effect is the expected number of times the effect occurs in a year in an 'average' subject, *n*. The relation of *n* with L_{night}* is discussed in this section. It is more complex than the relation of *chronic* effects with L_{night}*. For example, the chronic effect high self-reported sleep disturbance (*%HSD*) can be directly related to L_{night}* by the exposure-response function.

In order to relate n to L_{night}*, it is assumed that the effects of the individual noise events are independent. Then the maximum of n for a given L_{night}* is (see Appendix):

$$n_{max} \;=\; 10^{(Lnight^* - sel^* + 70.2)/10} \times \mathrm{f}(sel^*),$$

where the exposure–response function f gives the expected number of instantaneous effects caused by a single event as a function of SEL^* (it is a probability function if an event causes the effect or not). sel^* is the 'average' SEL^*, *i.e.,* $sel^* = L_{night}^* - 10\mathrm{lg}N + 70.2$, so that the first term of the multiplication reduces to N, the number of events.
If N and hence the 'average' sel^* is unknown, then the maximum of the above function over sel^* can be used as an upper bound for the expected number of instantaneous effects with a given L_{night}*. The value where the function is maximal, sel_0^*, is the solution of $\mathrm{f}'(SEL^*) = 0.23\times\mathrm{f}(SEL^*)$ where f' is the derivative of f (see Appendix). In many cases, the relevant (lower) part of the (probability) function can be approximated with sufficient accuracy by a quadratic function $\mathrm{f}(SEL^*) = \mathrm{a}\,SEL^{*2} + \mathrm{b}\,SEL^* + \mathrm{c}$. Then,

$$sel_0^* \;=\; 4.34 - \mathrm{A} + [(\mathrm{A} - 4.34)^2 - (\mathrm{c/a}) + 8.68\mathrm{A}]^{½},$$

where A = b/(2a).
Thus, when f is a quadratic function, then the maximal expected number of instantaneous effects in a year for a person exposed to a given L_{night}* is found by inserting this L_{night}* and the above sel_0^* in the equation for n_{max}. If L_{night}* is known to be caused by N events, then the (much lower) upper bound of the expected number of effects can be found by setting $sel^* = L_{night}^* - 10\ \mathrm{lg}N + 70.2$ in the equation for n_{max}.

If not *SEL* but L_{max} is assessed, appropriate empirical relationships between L_{max} and *SEL* can be used to find *SEL* on the basis of L_{max}. An example is the equation $SEL = 23.9 + 0.81\times L_{max}$ for outdoor values found by Ollerhead et al. (1992) for aircraft noise events. Also, the following relationships can be used to estimate *SEL* for transportation noise (see Appendix for details). If the shape of the time pattern of the sound level can be approximated by a block form, then $SEL \approx L_{max} + 10\mathrm{lg}t$, where t (in s) is the duration of the noise event. This rule can be used, e.g., for a long freight train that passes at short distance. When t is in the range from 3 to 30 s, then *SEL* is 5 to 15 dB(A) higher than L_{max}. For most passages of aircraft, road vehicles, or trains, the shape of the time pattern of the sound level can be better approximated with a triangle. If the sound level increase with rate a (in dB(A)/s), thereafter is at its maximum for a short duration before it decreases with rate $-a$, then $SEL \approx L_{max} - 10\mathrm{lg}a + 9.4$. Depending on the distance to the source, for most dwellings near transportation sources the rate of increase is in the order of a few dB(A)/s up to 5 dB(A)/s. When a is in the range from 9 to 1 dB(A)/s, then *SEL* is 0 to 9 dB(A) higher than L_{max}.

4 RELATIONSHIPS BETWEEN NIGHT-TIME NOISE AND MOTILITY

4.1 Measurement and meaning of motility

Measurement
Motility (movement) is measured with an actimeter, usually worn on the wrist. Measures of the accelerations associated with movements in the successive time intervals are stored in the memory of the actimeter. Usually the measurement interval is chosen between 2 and 60 s. If the accelerations during an interval exceed a threshold (which is, dependent on the type of actimeter, usually about 0.01 ms^{-2}), a positive value is stored and if the accelerations are below threshold, the value 0 is stored. The threshold is such, that the motility of active people while awake exceeds the threshold in nearly all intervals: the probability of motility in a 15-s interval during time awake is over 0.90. During sleep, motility is strongly reduced. For example, in the Netherlands sleep disturbance study, motility (over threshold) of all subjects while asleep occurs in 3.66% of the measurement intervals of 15-s, i.e., the probability of motility during sleep was 0.0366 (Passchier-Vermeer et al., 2002). The number of 15-s intervals in the average sleep period of 7 h and 10 minutes in that study population is 1720. Thus, the number of 15-s intervals with motility over threshold during the average sleep period is 63, and the number without motility is 1657. Another measure frequently used is the probability of *onset* of motility above threshold. The number of 15-s intervals during sleep with onset of motility above the threshold is equal to 40 (probability is equal to 0.0234) in the study mentioned. With other measurement intervals, the values of probability of (onset of) motility during sleep change accordingly. E.g., for 30-s intervals the probability of motility and of onset of motility in the study population mentioned would have been 0.072 and 0.047, respectively. There is a large inter-individual variability in the number of intervals with motility during the sleep period. Motility of elderly people is larger than motility of younger people (see also figure 4.4), males have a somewhat higher motility during sleep than females.

Meaning
Motility is related to many variables of sleep and health (Reyner, 1995; Reyner and Horne, 1995; Patterson et al., 1993). Clinical research shows that the sleep-wake cycle (assessed by polysomnography EEG, EOG, EMG) passes through the 24-hour period synchronously with the rest-activity cycle (assessed by actimetry) (Borbeley et al., 1981; Cole et al., 1992, 1995). A number of investigations have compared the results of polysomnographic recordings (number of EEG-awakenings during sleep period, duration of sleep period, sleep onset time, wake-up time) with results of actimetry. The correlation between actimetrically assessed duration of sleep period, sleep onset time, wake-up time and similar variables assessed with polysomnography were found to be very high (correlation coefficients between individual test results in the order of 0.8 to 0.9).

Motility during sleep is also associated with responses to questionnaires and in diaries (Passchier-Vermeer et al., 2002). Significant associations have been found between mean (onset of) motility during sleep and the following variables:

- frequency of behavioural awakening during the sleep period. The increase is 0.8 behavioural awakenings per night, if motility increases from low to high;

- frequency of awakening remembered next morning. The increase is 0.5 remembered awakenings per night, if motility increases from low to high;
- long-term frequency of awakening attributed to specific noise sources assessed with a questionnaire;
- sleep quality reported in a morning diary;
- long-term sleep quality assessed with a questionnaire;
- number of sleep complaints assessed with a questionnaire;
- number of general health complaints assessed with a questionnaire.

The associations of mean motility with these variables are much stronger than the corresponding associations of mean onset of motility.

4.2 Information regarding exposure-effect relationships

Reviews of the literature on noise-induced instantaneous motility or awakenings found a much higher response in the laboratory than in field studies (Pearsons, 1989; Pearsons et al., 1995). Partly these differences are due to differences in data collection methods and ways to measure effects, but they are also a consequence of the different reactions to noise in both situations. Since the exposure-effect relationships in this report are meant for the prediction of effects on residential populations, this chapter on motility only takes the results of field studies into account. Sections 4.3 and 4.4 give the following relationships between noise exposure and motility that are based on field studies (also see table 4.1):

- Increase in probability of (onset of) motility as a function of descriptors of single noise events ($L_{max}*$, $SEL*$).
- Increase in mean motility during the sleep period as a function of noise exposure during this period ($L_{night}*$).

This section reviews the (large-scale) field investigations which have been undertaken during the last decade:

- Ollerhead et al, 1992
- Fidell et al., 1995
- Fidell et al., 1998, 2000
- Griefahn et al., 1999
- Flindell et al., 2000
- Smith et al., 2001
- Passchier-Vermeer et al., (2002).

Table 4.1: Variables to which motility is related in this chapter.

$L_{night}*$	L_{Aeq} in the bedroom during the individual sleep period (in dB(A))
$SEL*$	SEL in the bedroom (in dB(A))
$L_{max}*$	L_{max} in the bedroom (in dB(A))
Age	age (in years)
Age^2	square of age

Table 4.2 gives information about some aspects of the studies. A short overview of the studies is given after the table. Only general information is included, and information about the relation between motility and traffic noise exposure. Results obtained by

questionnaires, morning and evening diaries and results obtained by polysomnography or other physiological measurement methods are not included in this section.

Table 4.2: Overview of field studies of the last decade.

	Ollerhead et al.,1992 Horne et al., 1994	Fidell et al., 1995b	Fidell et al., 1998	Griefahn et al., 1999	Flindell et al., 2000	Smith et al., 2001	Passchier-Vermeer et al., 2002
Noise source	Aircraft	Aircraft	Aircraft	Road traffic and railway	Aircraft	Environmental	Aircraft
Number of subjects	400	77	22	377	18	90	418
Number of subject nights for analysis	5742	2717	686	2648 (original number 3263)	5	3	4528
Number of outdoor or indoor noise events*subjects for analysis	Outdoor: 31000 (original number according to Ollerhead: 87729, according to Horne 121534)	Indoor: 43934	Indoor: 1472	Not applicable	-	Indoor 1980	Indoor: 63242
Duration of measurement interval of actimetry	30 s	30 s	30 s	125 ms, 2 s, 30 s	-	5 s	15 s
Effects considered during	Sleep period between 23.30 and 5.30 hours	Sleep period between 22 and 7 hours	Sleep period between 22 and 7 hours	Sleep period between 22 and 8 hours	-	Sleep period between 23 and 8 hours	Sleep period between 22 and 9 hours

Ollerhead et al. (1992), Horne et al. (1994)

In the UK, the first large scale field study on sleep disturbance investigated the effects of night-time aircraft noise on motility in 211 women and 189 men, 20-70 years of age, living at one of eight locations near four UK airports with different levels of night flying. Subjects wore actimeters for 15 nights. In a sample of 178 nights EEG's were recorded synchronously with actigrams. Noise measurements have been performed outdoors only. A noise event that exceeded 60 dB(A) and simultaneously triggered three outdoor noise monitors was compared with air traffic control logs to identify aircraft overflights and to determine landing/taking-off, route and aircraft type. A 30-s interval with onset of motility was called an A-blip. The probability of an A-blip in a 30-s interval with the maximum of an aircraft noise event was designated as n, the probability of an A-blib in other 30-s intervals was designated q. It was found that q = 0.051. According to Ollerhead et al., the probability of an aircraft noise event causing an A-blip is equal to n - q. Figure 4.1 shows n - q as a function of L_{max}. Ollerhead et al. state that n – q is significantly larger than 0 for $L_{max} \geq 82$ dB(A). Horne et al. (1994) suggest that the difference between L_{max} and $L_{max}*$ at the study locations is on average about 20 dB(A). However, probably the difference between L_{max} and $L_{max}*$ is location-dependent, since at the two locations with the highest night-time aircraft noise L_{Aeq} (66.5 and 61.5 dB(A))

90% of the dwellings had bedroom windows with double or triple glazing, and at the locations with lower exposure (between 43 and 55 dB(A)) the percentages of double-glazed bedroom windows varied from 10 to 90%, with an average of 50%.
Ollerhead et al. did not investigate mean motility during sleep.

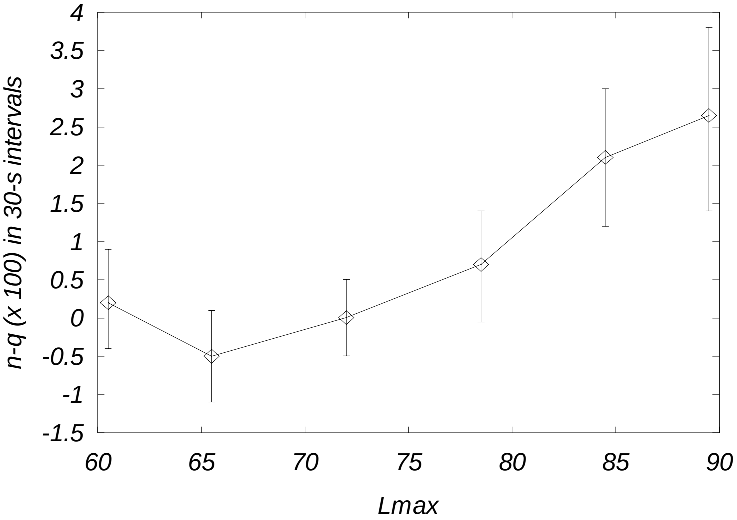

Figure 4.1: N-q (x 100) as a function of outdoor L_{max}. Vertical bars are 95% confidence intervals, (Ollerhead et al., 1992).

Fidell et al. (1995b)

This field study on aircraft noise-induced disturbance was conducted in the vicinity of Stapleton International Airport (DEN) and of Denver International Airport (DIA) during the period of transition in flight operations from the closing of DEN to the opening of DIA. Subjects were selected from locations as close as feasible to the runway ends. Fidell et al. state that because no effort was made to obtain a representative sample of any population, conclusions drawn from the study strictly apply to the test participants only.

Noise measurements have been performed outdoors and inside bedrooms. An outdoor and an indoor noise event was taken into account, if the sound level exceeded 60 and 70 dB(A), respectively, for at least 2-s. No attempt was made to eliminate noise events from sources other than aircraft from the analyses.

Fidell et al. found the following relationship between *SEL** and probability of motility measured within 5 minutes (i.e., 10 30-s intervals) during and after a noise event: *%motility* = -23.74 + 1.23 *SEL**.

Mean motility during a 30-s interval is equal to 0.056 according to the report. This implies that the probability of absence of motility in a 30-s interval is (1 – 0.056), and in 10 consecutive 30-s intervals $(1 - 0.056)^{10} = 0.562$. Consequently, the probability of motility during 10 consecutive 30-s intervals is equal to 1 - 0.562 = 0.438 (43.8%).

From the formula above, it follows that for $SEL^* > 55$ dB(A), during 10 30-s intervals: *%noise-induced motility* = $1.23\times(SEL^*-55)$.

Fidell et al. also tried to replicate the analyses performed by Ollerhead et al., by using the data of 27 subjects collected prior to the closing of DEN. The probability of an A-blip in a 30-s interval could be predicted on the basis of four variables (individual susceptibility, age, self-reported tiredness, and sequential night of data collection), but no improvement in the prediction was obtained by including *outdoor* noise descriptors (L_{max} or SEL). This implies that it could not be shown that *outdoor* (aircraft) noise is a determinant of onset of motility. Fidell et al. did show that descriptors of *indoor* noise (L_{max}^* and SEL^*) are determinants of motility. A predictive model included two categories of *indoor* noise event levels (L_{max}^* less than 65 dB(A), L_{max}^* at least 65 dB(A)), individual sensitivity, age, months of residence, and self-reported tiredness.

Fidell et al. (1998, 2000)

A small field study was conducted in the vicinity of DeKalb-Peachtree Airport (PDK), a large general aviation airport north of Atlanta, Georgia, beginning 2.5 weeks before the start of the Olympic Games near Atlanta and ending one week after the end of the games. Indoor and outdoor measurements of aircraft and other night-time noises were made in twelve homes. The same thresholds (60 and 70 dB(A)) for indoor and outdoor noise events as in the 1995 study were used.

A relationship between SEL^* and motility was found, using an algorithm from Cole et al. (1992).

Griefahn et al. (1999)); Möhler et al. (2000)

In Germany for railway traffic an adjustment of –5 dB(A) is applied to equivalent sound levels to obtain rating levels. This adjustment is 0 dB(A) for road traffic noise. These adjustments have been based on exposure-effect relationships for noise annoyance. The main objective of the German study was to determine whether this adjustment of –5 dB(A) for railway noise is also justified with a view to differences in sleep disturbance caused by road and railway traffic.

The study has been carried out at eight locations, four locations with predominant road traffic noise and four locations with predominant railway noise. At each location subjects took part during ten nights (two times 5 nights from Sunday night to Friday morning). The distribution of the subjects over the rating levels was more or less equal for the two noise sources. Subjects were from 18 to 66 years of age, and lived for 1 to 64 years in the present neighbourhood.

Motility was assessed with the same actimeters as used in the UK field study on aircraft noise (Ollerhead et al. (1992); Horne et al. (1994)). Polysomnography (EEG, EOG, EMG) was performed with 238 subjects during one night (225 registrations could be used for comparison with motility data). Several effect variables pertaining to a sleep period have been derived from the stored actimetric data, such as:

- percentage of 2-s intervals during the sleep period with motility;
- percentage of 30-s intervals during the sleep period with motility;
- percentage of 30-s intervals during the sleep period with onset of motility.

The acoustic measurements showed that road and railway traffic on Monday through Thursday nights was about the same, but that equivalent sound levels of railway traffic during Sunday nights was about 10 dB(A) lower than on other nights. To meet the requirement of about equal rating levels for road and railway noise, only the actimetric data obtained on Monday through Thursday nights have been analysed (2648 of the 3263 usable actigrams).

It was found that subjects exposed to railway noise show on average (averaged over subjects and sleep period times) motility in 6.7±2.3 % of the 30-s intervals at railway locations, and in 6.5±2.2 % of the 30-s intervals at road traffic locations. No exposure-effect relationships have been established, since this was outside the scope of the study.

Flindell et al., (2000)
The publication of Flindell et al. refers to a research trial on sleep disturbance to evaluate research options for further investigation. In the field pilot investigation 18 subjects participated for 5 nights. The publication did not aim at presenting exposure-effect relationships.

Smith et al., (2001)
In a small part of a large field and laboratory study by Smith et al., the use of actimetry has been explored with 90 subjects for three nights. The noise source has been described as environmental noise. Noise events have been separated in events of short (less than 60 s) and longer duration. The results of the actimetric measurements during sleep period (among others: sleep duration, sleep efficiency, fragmentation index, mean motility) have been compared with results of indoor noise measurements. Relationships of exposure with instantaneous effects have not been established. For the group as a whole, noise exposure was low. The results showed that there were no significant associations between noise and motility variables. The authors state: “This probably reflects the low level of noise as associations in other studies are found with louder noise exposure”.

Passchier-Vermeer et al, (2002)
The subjects in this study were exposed to night-time aircraft noise as it usually occurs in their bedroom. Ages of subjects varied between 18 and 81 years, 50% of the subjects was male, 6% lived less than 1 year in the present neighbourhood, 44% over 15 years and the remaining 50% between 1 and 15 years. The study has been carried out at 15 locations within a distance of 20 km from Schiphol. The locations were selected so that there was a variation from relatively few aircraft at night up to the highest exposure in residential areas, close to the airport. At each location, the study took place during two subsequent intervals with 11 nights.
To assess night-time (aircraft) noise exposure of subjects, noise measurements have been performed from 22 – 9h with indoor noise monitors in the bedroom of each subject and with one outdoor noise monitor. The noise monitors stored each second the equivalent sound level. Aircraft noise events were identified by comparing the noise and time data stored in the indoor and outdoor noise monitors with information obtained from the aircraft identification system at Schiphol (FANOMOS).
The report presents relationships between night-time aircraft noise exposure and motility for three time scales:

- On the instantaneous level: instantaneous (onset of) motility during sleep has been related to L_{max}* and *SEL**. The (onset of) motility during 7 15-s intervals has been analysed: the 15-s interval at which the maximum sound level occurs, 2 15-s intervals preceding that interval, and 4 15-s intervals following that interval. Aircraft noise-induced (onset of) motility has been assessed by subtracting from the probability of (onset of) motility during these 15-s intervals the probability of (onset of) motility in 15-s intervals without aircraft noise. Aircraft noise-induced increase in motility is maximal in the 15-s interval with the maximum noise level of the overflight and in the subsequent interval. Aircraft noise-induced increase in onset of motility is, at higher values of L_{max}*, maximal in the 15-s interval preceding the 15-

s interval with the maximum noise level and somewhat less in the 15-s interval with the maximum noise level. No exposure-effect relationships could be derived if descriptors of outdoor aircraft noise were taken as predictors.
- On the level of a sleep period: mean motility during a sleep period has been related to the equivalent aircraft sound level in that period. It was shown that mean motility increases with indoor aircraft equivalent sound level. Also, duration of sleep latency time has been related to aircraft equivalent sound level during sleep latency time.
- On a long-term basis: mean (onset of) motility over the 11 sleep periods has been related to L_{night}*.

Conclusion

To have sufficient power to assess relationships between noise exposure and instantaneous effects, very large databases must be collected, handled, and analysed. Furthermore, the repeated measurements with the same subjects introduce dependencies between the outcomes which have to be taken into account in the analyses. This requires large data storage and data manipulation facilities, and sophisticated analyses techniques. Improved facilities and techniques have become commercially available recently. At the time of the Netherlands aircraft noise study, for which the data have been analysed in 2001 and 2002, the available facilities and techniques had advanced considerably compared to the situation at the time of the UK aircraft noise study. Related to this, first exposure-effect relationships of the Netherlands aircraft noise study are presented in this report, since we consider them to represent the best currently available knowledge of exposure-effect relationships for motility. Thereafter a comparison is made with the exposure-effect relationships found in other motility studies. The exposure-effect relationships presented have been derived for aircraft noise.

4.3 Relationships between *SEL** or L_{max}* and instantaneous motility.

In Passchier-Vermeer et al. (2002) relationships between noise-induced increase in motility (*m*) or noise-induced increase in onset of motility (*k*) in the 15-s interval with the maximum noise level of an overflight, and L_{max}* or *SEL** have been approximated by quadratic functions with the following format:

$$m \;=\; \mathrm{b}(L_{max}{*} - \mathrm{a}) + \mathrm{c}(L_{max}{*} - \mathrm{a})^2$$

The coefficients a, b and c are given in table 4.3. The value of a is the value below which *m* or *k* is zero. Figure 4.2 shows the relationship between *m* and L_{max}* together with the 95% confidence interval. Relations apply to L_{max}* and *SEL** values of at most 70 and 80 dB(A), respectively.

Table 4.3: Coefficients of the quadratic equation of *m* and *k* as a function of L_{max}* or *SEL** for the 15-s interval in which indoor maximum sound level of an aircraft noise event occurs (see text). The equations are applicable in the L_{max}* range from 'a' up to 70 dB(A), or *SEL** range from a up to 80 dB(A). Below 'a', *m* and *k* are zero.

	(Aircraft) noise-induced increase of probability of motility (*m*)	(Aircraft) noise-induced increase of probability of *onset* of motility (*k*)
	$32 < L_{max}* < 70$ dB(A)	$32 < L_{max}* < 70$ dB(A)
a	32	32
b	0.000633	0.000415
c	3.14×10^{-5}	8.84×10^{-6}
	$38 < SEL* < 80$ dB(A)	$40 < SEL* < 80$ dB(A)
a	38	40
b	0.000532	0.000273
c	2.68×10^{-5}	3.57×10^{-6}

One of the variables influencing the relationships between noise-induced motility, and L_{max}* or *SEL** is the individual long-term aircraft noise exposure during sleep. This is illustrated in figure 4.3. In a situation with indoor L_{night}* equal to 0 dB(A), subjects are, e.g., exposed each night to one aircraft with indoor L_{max}* equal to 35 dB(A) or each week to one aircraft with indoor L_{max}* equal to 44 dB(A). The figure shows that with higher aircraft noise exposure (L_{night}* equal to 40 dB(A)), the probability of instantaneous aircraft noise-induced increase in motility is much lower. The values in table 4.3 are the estimaties of the parameters when $L_{night}* = 26$ dB(A).

Other determinants of the relationships between instantaneous motility and L_{max}* or *SEL** are the point of time in the night, and time since sleep onset. E.g., after 7 hours of sleep noise-induced motility is about 1.3 larger than in the first hour of sleep. Age has only a slight effect on noise-induced motility, with younger and older people showing a lower motility response than persons in the age range of 40 to 50 years.

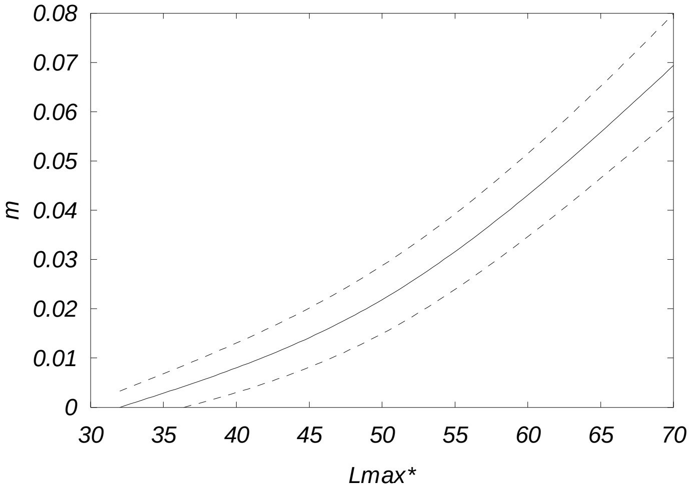

Figure 4.2: Probability of (aircraft) noise-induced motility (m) at the 15-s interval in which the indoor maximum sound level occurs (solid line) and the 95% confidence interval, as a function of L_{max}* (Passchier-Vermeer et al., 2002).

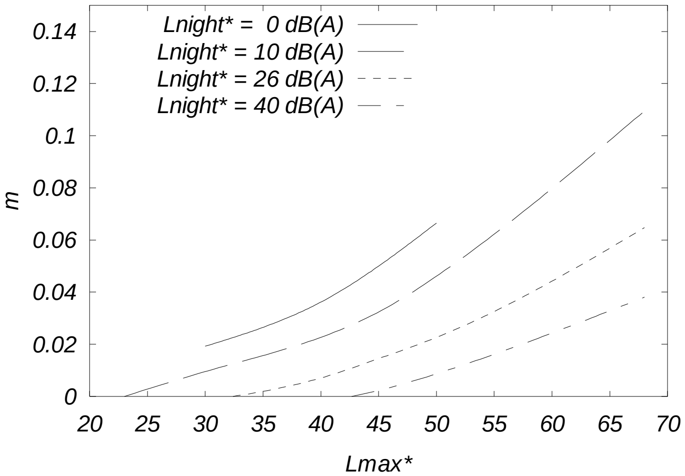

Figure 4.3: Probability of (aircraft) noise-induced motility (m) in the 15-s interval at which indoor maximum noise level occurs as a function of L_{max}*, for various levels of long-term aircraft noise exposure during sleep period (L_{night}*) (Passchier-Vermeer et al., 2002).

4.4 Relationships between L_{night}* and long-term motility

Mean motility during sleep is strongly related to age and is also a function of noise exposure during the sleep period. The relationships between mean motility and L_{night}* are shown in figure 4.4 for three ages. Mean motility during sleep is lowest at an age of 45 years, and is larger at lower and higher ages. The relation between mean motility, and L_{night}* and age is:

$$\textit{Mean motility} \quad = \quad 0.0587 + 0.000192 \times L_{night}^* - 0.00133 \times age + 0.0000148 \times age^2.$$

The relation between mean noise-induced motility, m_{night}, and L_{night}* is:

$$m_{night} = \quad 0.000192 \times L_{night}^*.$$

The increase in m_{night} is 0.0067 if indoor L_{night} increases from 0 to 35 dB(A), independent of age.

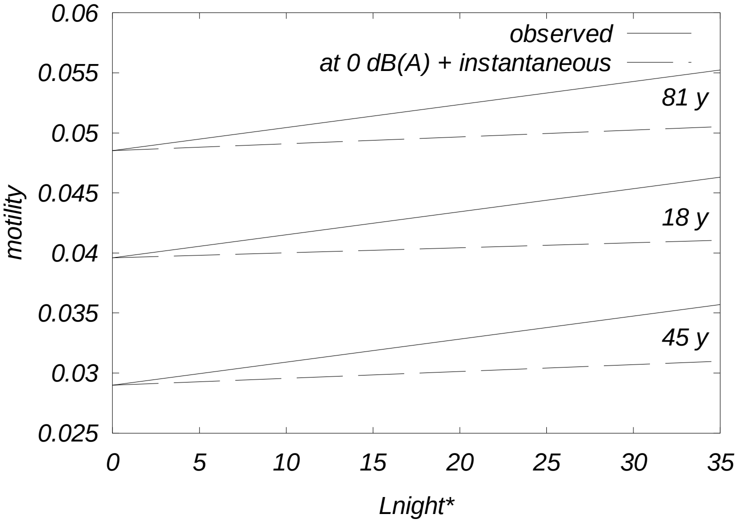

Figure 4.4: Mean motility during the sleep period as a function of indoor L_{night}* for three ages: 18 years, 81 years, and 45 years (the age at which mean motility is lowest). Observed mean motility, and mean base rate motility increased by instantaneous reactions to noise events are given. The difference between the two lines for one age represents the extra motility induced by noise but not as a direct response to a noise event.

The noise-induced mean motility, m_{night}, has two components (see figure 4.4):

- The instantaneous increase in motility at the time of aircraft noise events during sleep. The increase in mean motility during sleep as a result of the instantaneous motility responses varies from 0 in the absence of aircraft noise up to 0.002 when L_{night}* = 35 dB(A);

- A long-term component, i.e. the difference between the observed mean motility and the base rate plus the instantaneous component of noise-induced motility.

4.5 Comparison with results of other field studies

Ollerhead et al. (1992), Horne et al. (1994)
Figure 4.5 shows the results of the UK and Netherlands aircraft noise study. The probability of onset of motility in 15-s intervals, found in the Netherlands study have been recalculated for 30-s intervals. For the UK-study indoor L_{max}* is estimated by subtracting an 'average bedroom sound insulation' of 20 dB(A) from L_{max} (Horne et al., 1994).

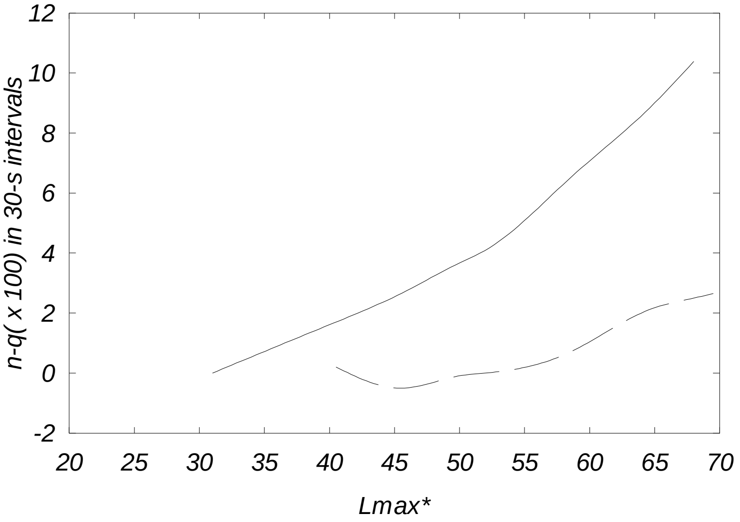

Figure 4.5: The relationships found in the Netherlands aircraft field study (solid line) and in the UK aircraft field study (broken line).

The following factors have contributed to an underestimation of the effect of aircraft noise on onset of motility in the UK study.

- No indoor noise measurements have been performed. To estimate indoor L_{max}*, as suggested by Horne et al. (1994) 20 dB(A) has been subtracted from the outdoor L_{max}. The percentage of bedroom windows with double-glazing at a location varied from 10 to 90%. Therefore, the difference between L_{max} and L_{max}* may be on average larger than 20 dB(A). If a sound insulation of 25 dB(A) would be subtracted to take into account the 'sound insulation' of the bedroom, the UKD curve would have shifted 5 dB(A) to the left. Moreover, since 90% of the bedroom windows at the locations with the highest aircraft noise exposure had double- or triple-glazing, it is likely that the difference between L_{max} and L_{max}* at those locations is larger than the difference at the other locations so that the actual curve for onset of motility is steeper than the curve for the UK study shown in figure 4.5.

- The threshold for a noise event of 60 dB(A) outdoors implies that all 30-s intervals with (aircraft) noise events below 60 dB(A) are considered as quiet. Effects on onset of motility of these lower (aircraft) noise events increase q. The same applies to noise events over threshold, if they have not been identified as aircraft noise events.
- Especially when $L_{max}*$ is high, noise-induced motility may start before the 30-s interval with the maximum of the event (Passchier-Vermeer et al., 2002). In those cases *onset* of motility is absent in the 30-s interval with $L_{max}*$. This implies that the aircraft noise-induced onset of motility has not been completely attributed to n, but in part has been added to q.
- In the analysis, aircraft noise events which occurred within 5 minutes after a preceding event were omitted. It is unclear whether the 30-s intervals have been considered as quiet and possible effects have contributed to q.
- Due to limitations of computer facilities in 1992, only aircraft noise events that occurred between 23.30 and 5.30 hours have been considered. However, probability of aircraft noise-induced motility increases with time of the night, which implies an underestimation of the overall effect of noise exposure, since events after 5.30 h have not been taken into account.
- There may be a small effect of aircraft noise events that are assigned to the wrong 30-s interval. It is stated that all recording instrumentation (noise, EEG, and actimetry) was synchronised. The aim was to ensure that no instrument ever had a time drift exceeding 15 s. This implies that time differences between noise monitors and actimeters may have exceeded 30-s in presumably exceptional cases.
- No indoor noise measurements have been performed. Other studies showed that indoor noise event measures have a much stronger relationship with (onset of) motility than outdoors measures (Fidell et al, 1995b, 1998; Passchier-Vermeer et al., 2002).

Fidell et al. (1995b)

The relationship between $SEL*$ and probability of motility measured within 5 minutes (i.e. 10 30-s intervals) can be given by: $\%motility = 1.23(SEL* - 55)$. To compare this result with the exposure-effect relationships, the following assumptions are made (Passchier-Vermeer et al., 2002):

- 30% of the noise-induced increase in motility within 5 minutes after noise event onset occurs during the 15-s interval with the maximum sound level of the event.
- $SEL* = 80$ dB(A) corresponds to $L_{max}* = 70$ dB(A).

Then, probability of noise-induced increase in motility during the 15-s interval with the maximum sound level of the event (m) is equal to $0.30 \times 1.23 \times (L_{max}* - 45)/100 = 0.0037(L_{max}* - 45)$. Thus, for $L_{max} = 45$ dB(A), $m = 0$ and for 68 dB(A), $m = 0.0851$. Because subjects lived at locations very close to the runway ends of the airports, it is reasonable to assume that subjects are highly exposed to aircraft noise. Figure 4.6 compares the exposure-effect relationships.

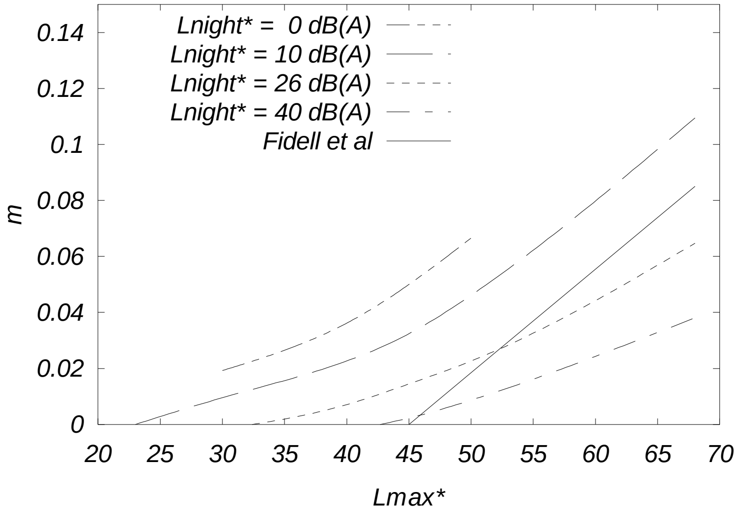

Figure 4.6: The relationships (based on the results) of Fidell et al. (1995) (solid line) and the relationships from the Netherlands aircraft field study for different long-term aircraft equivalent sound levels

According to Fidell et al., probability of motility onset in the 68832 30-s intervals with L_{max}* below 65 dB(A) (including intervals without noise events) is 0.056, and for the 72 30-s intervals with L_{max}* at least 65 dB(A) 0.240. This is an increase in probability of motility onset of 0.18. For a measurement interval of 15-s, probability of motility onset would be 0.09. This value is in good agreement with the relationship specified in table 4.3: aircraft noise-induced increase of onset of motility is 0.09 when L_{max}* = 66 dB(A).

Fidell et al. (1998)

The relationship between *SEL** and motility as calculated with an algorithm from Cole et al. (1992) cannot be transformed into the type of exposure-effect relationship presented in this report.

Griefahn et al. (1999)

In the German study no exposure-effect relationships have been established, since this was outside the scope of the study.

Flindell et al., (2000)

The objective of this study on sleep disturbance was to evaluate research options for further investigations, and did not aim at presenting exposure-effect relationships.

Smith et al., (2001)
The study did not show any statistically significant associations between noise and motility (sleep) variables.

4.6 Relationships of instantaneous and mean motility with L_{night}

Section 4.3 presented the relationship between (indoor) SEL^* and instantaneous motility. This relationship is used here to find, with the aid of the results from section 3.3, the relationship between (outdoor) L_{night} and the maximal expected number of intervals with motility, n_{max}. Section 4.4 presented the relationship between (indoor) $L_{night}{}^*$ and the mean noise-induced motility, m_{night}. This is reformulated here to give the corresponding relationship between (outdoor) L_{night} and m_{night}.
n_{max} as a function of L_{night} is found by substituting the function for noise-induced instantaneous motility in the equation for n_{max} in section 3.3. To find the function f for noise-induced instantaneous motility, the function that gives the instantaneous motility in the 15-s interval with the maximum of a noise event, with $SEL10^*$ of that event as the independent variable, given in section 4.3 (table 4.4), is rewritten into the form $\mathrm{a}SEL10^{*2} + \mathrm{b}SEL10^* + \mathrm{c}$, giving $0.0000268SEL10^{*2} - 0.0015048SEL10^* + 0.0184832$. Then, using that for the aircraft overfights $\mathrm{SEL}^* \approx \mathrm{SEL10}^* + 2$ and the expected extra motility caused by an overflight is circa 4.6 times the probability of the extra motility in the interval with the maximum sound level, it is found that:

$$\mathrm{f}(SEL^*) = 4.6[\,0.0000268\times(SEL^*-2)^2 - 0.0015048\times(SEL^*-2) + 0.0184832],$$

which after simplification gives:

$$\mathrm{f}(SEL^*) = 0.0001233\times SEL^{*\,2} - 0.007415\times SEL^* + 0.0994.$$

Substituting this f in the equation for n_{max} in section 3.3 gives:

$$n_{max} = 10^{(Lnight^*-sel^*+70.2)/10}\times(0.0001233\times sel^{*\,2} - 0.007415\times sel^* + 0.0994).$$

Let $LDiff1$ be the difference between L_{night} (at the most exposed façade) and the similar L_{Aeq} at the façade of the bedroom, and $LDiff2$ the difference between the night-time L_{Aeq} outdoors at the façade of the bedroom and in the bedroom during the sleep period. Then $L_{night}{}^* = L_{night} - LDiff1 - LDiff2$ and $sel^* = sel - LDiff1 - LDiff2$, and the maximal expected yearly number of noise-induced motilities as a function of L_{night} and sel is:

$$\begin{aligned} n_{max} = \; 10^{(Lnight-sel+70.2)/10} \times [\,&0.0001233\times(sel - LDiff1 - LDiff2)^2 \\ &- 0.007415\times(sel - LDiff1 - LDiff2) \\ &+ 0.0994], \end{aligned}$$

or as a function of L_{night} and N:

$$\begin{aligned} n_{max} = \; N\times[\,&0.0001233\times(L_{night} + 70.2 - 10\lg N - LDiff1 - LDiff2)^2 \\ &- 0.007415\times(L_{night} + 70.2 - 10\lg N - LDiff1 - LDiff2) \\ &+ 0.0994], \end{aligned}$$

where N is the number of aircraft noise events above the effect threshold (in terms of outdoor L_{max}: > 53 dB(A)). The difference $LDiff2$ takes into account the actual use of windows. Default values for the differences are *LDiff1* = 0 dB(A) and *LDiff2* = 21 dB(A). The curves in figure 4.7 give n_{max} as a function of *sel** (= *sel –LDiff1–LDiff2*) for the values 25, 30, or 35 for L_{night}* (= L_{night} *–LDiff1–LDiff2*)

For the derivation of the above relationships for n_{max}, the effects of the individual noise events are assumed to be independent, and a person is assumed to sleep each night precisely during the period from 23 to 7h. Since the parameter estimates from table 4.3 are used for the derivation of the relationships, the 'habituation' of the instantaneous motility response that actually occurs at L_{night} *–LDiff1–LDiff2* = 26 dB(A) is assumed.

If the number of events and hence the average *sel** is known, then the above equations for n_{max} with the actual L_{night} can be used to find an upper bound of the expected number of 15-s intervals in a year with noise-induced motility. When the number of events is not known, then still the top of the curve can be found and taken as an upper bound for the expected noise-induced instantaneous motility. The top of the curve is found by substituting the above function f in the equation of sel_0* in section 3.3. For the motility function this gives sel_0* = 45.3 dB(A). The height of the top is 1600, 5100, 16100, respectively, which is found by substituting sel_0 *–LDiff1–LDiff2* = 45.3 dB(A) in the equation for n_{max}, while setting L_{night}* (= L_{night}*–LDiff1–LDiff2*) equal to 25, 30, or 35 dB(A), respectively. The corresponding numbers of noise events per night are 269, 851, and 2690, respectively. For aircraft noise these numbers of overflights usually do not actually occur in one night. Especially if L_{night}* is equal to 30 or 35 dB(A), aircraft noise events have *SEL** values that are larger than 45.3, and the maximum total number of noise-induced 15-s intervals with motility is given by the right tails of the curves which are considerably lower than the top.

The curves in figure 4.7 illustrate that a limit in terms of L_{night} implies an upper bound on the expected number of instantaneous noise-induced effects. Generally, the upper bound that can be found is lower if also the number of events and, hence, *sel* is known. An important feature of the curves is that sel_0, where the function is maximal, is relatively low. With a given L_{night}, the worst case regarding the incidence of instantaneous effects occurs when the events cause indoor *SEL** values just above the effect threshold. Consequently, extra protection in addition to a limit in terms of L_{night} cannot be provided with limits for *SEL* (or L_{max}), but requires limits for the number of events if the threshold of the effect is much lower than levels that can be prohibited. Since the threshold for noise-induced motility is low in this sense, extra protection with a view to this and associated effects would require restrictions on the number of events. Given a L_{night} limit, decreasing the number of events that are allowed, moves the 'average' *sel** further and further to the end of the right tail of a figure such as figure 4.7. E.g if the limit for L_{night} is 51 dB(A) and the number of noise events allowed per night is 8.5 (a factor 100 lower than in the worst case with an unrestricted number of events), then a situation with all noise events with *SEL** equal to 65.3 dB(A) is the worst case (with 440 effects expected instead of 5100 in the worst case with an unrestricted number of events).

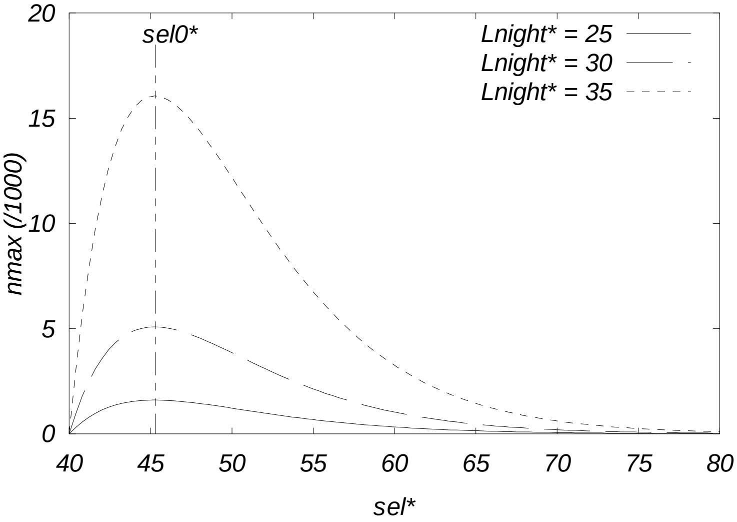

Figure 4.7: The curves give the maximum expected number of 15-s intervals with noise-induced motility, n_{max}, as a function of sel^* (average SEL^*) for L_{night}^* equal to 25, 30, or 35 dB(A), respectively. The curves have their maximum at $sel_0^* = 45.3$ dB(A).

The following relationship with outdoor L_{night} follows directly from the relationship that has been presented in section 4.4 for the noise-induced mean motility, m_{night}, as a function of the indoor L_{night}^* :

$$m_{night} = 0.000192\times(L_{night} - LDiff1 - LDiff2).$$

Again, the default values $LDiff1 = 0$ dB(A) and $LDiff2 = 21$ dB(A) can be used.

5 RELATIONSHIPS BETWEEN NIGHT-TIME NOISE AND SELF-REPORTED SLEEP DISTURBANCE

5.1 Introduction

Relationships between noise exposure and noise annoyance have been established in comprehensive meta-analyses (see: Schultz; 1978, Kryter, 1982, 1983; Fidell et al., 1991; Miedema and Vos, 1998; Miedema and Oudshoorn, 2001). Similar comprehensive analyses to establish relationships between night-time noise and self-reported sleep disturbance have not been conducted. Many individual studies assessed night-time noise and self-reported sleep disturbance and analysed their relationship, but the individual results have not been synthesised, except by the Netherlands Health Council (1997). In this report an attempt will be made to improve this latter synthesis by adding new datasets, giving more attention to the comparability of the assessment of the night-time noise and the self-reported sleep disturbance in different studies, and by using a statisical model that is better suited for the type of data concerned. As a part of this project, the datasets in the comprehensive TNO archive have been analysed in order to establish relationships between night-time noise and self-reported sleep disturbance. The relations between night-time noise and self-reported sleep disturbance are presented in section 5.4, after the analysis model (section 5.2) and the data (section 5.3) have been described. In subsequent sections (5.5 – 5.8) the role of factors other than a single night-time exposure metric is explored.

5.2 Exposure-effect model

The statistical model developed for the analysis of the relationship between noise exposure and noise annoyance (Miedema and Oudshoorn, 2001) is used here to model the relationship between self-reported sleep disturbance and L_{night}. We refer to the above article for the description of the model. With this model the relationships for the percentage highly sleep disturbed *(%HSD*), the percentage sleep disturbed *(%SD*), or the percentage (al least) a little sleep disturbed (*%LSD*) can be calculated as follows (Equation 5.1):

$$P_C(L_{night}) \;=\; 100 \times (1 - \Phi((C - [b_0 + b_1 L_{night}]) / \sqrt{}(s^2 + s_0^2))),$$

where $P_C(L_{night})$ is the estimated percentage of persons exposed to L_{night} with a sleep disturbance score (scale 0-100) above cutoff point C, Φ is the cumulative normal distribution, and b_0, b_1, s^2, s_0^2 are the four model parameters. Parameter s^2 represents the variance of the individual responses at a given L_{night}, while s_0^2 represents the between study variance. It is not always possible or desirable to distinguish these two components of variability, so that sometimes a single parameter s^2 that incorporates both components is used. The parameters b_0, b_1, s^2, s_0^2 need to be estimated on the basis of data. The *%HSD* at a given L_{night} is obtained by substituting the estimates of the parameters in the above equation and by substituting 72 for C. When 50 is substituted for C then the estimate of *%SD* is obtained, and substituting 28 gives *%LSD*. These cutoffs (72, 50 and 28) are analogous to the cutoffs 72, 50 and 28 that are used for calculating the percentage highly annoyed (*%HA*), the percentage annoyed (*%A*) and the percentage (at least) a little annoyed (*%LA*) by noise.

In addition to investigating the influence of L_{night} (at the most exposed façade) on self-reported sleep disturbance, the influence of age and factors that further specify the acoustical situation (see table 5.1) is investigated. For the analysis of the influence of additional variables, the following extension of the model is used (Equation 5.2):

$$P_C(L_{night}) = 100 \times (1 - \Phi((C - [b_0 + b_1 L_{night} + \Sigma_i\, b_i X_i]) / \sqrt{}(s^2 + s_0^2))),$$

where X_i is an additional predictor of sleep disturbance.

Table 5.1: Predictors of self-reported sleep disturbance that are investigated in different analyses.

Variable	***Definition***
Rail	1 = railway is the source, 0 = other source
Rail x *L*	product of *Rail* and L_{night} (in dB(A))
LDiff1	L_{night} most exposed façade minus similar L_{Aeq} façade bedroom (in dB(A))
Pos1	1 = façade bedroom perpendicular to road/rail, 0 = else
Pos2	1 = façade of bedroom facing direction opposite to road/rail or no view on road/rail from bedroom, 0 = else
LIso	insulation of the bedroom (in dB(A))
Win	1 = double glazing or special (insulated) windows, 0 = else
LDiff2	outdoors L_{Aeq} minus L_{Aeq} in bedroom for sleeping period (in dB(A))
$L_{07\text{-}23h}$	daytime L_{Aeq} at the most exposed façade (in dB(A))
LSource2	L_{night} of second source (in dB(A))
Age	age (in years/100)
Age^2	square of age (with age in years/100)

5.3 Data

TNO has compiled an archive of original datasets from studies on annoyance caused by environmental noise[2], which are used here to estimate the parameters of the model specified by the Equations 5.1 and 5.2. These studies concerned different modes of transportation (aircraft, road traffic, and railway) and were carried out in Europe, North America, Australia, and Japan. Two recent studies from France and Germany[2] both concerning road traffic and railway noise, and a recent aircraft noise study conducted in the Netherlands have been added to the archive within the framework of this project. As far as possible a common set of variables has been derived for each respondent from all

---

[2] We are grateful to all investigators who provided us with data from their studies. We especially thank INRETS and SNCF for their willingness to provide the data from their still very recent French study, and Möhler & Partner and DB for their willingness to provide the data from their still very recent German study.

studies which includes, among others, noise exposure measures (e.g., L_{night}) and self-reported sleep disturbance scores. Low exposure levels (L_{night} < 45 dB(A)) were excluded from the analyses because in general the assessment of those levels is relatively inaccurate and in situations with these low levels other sources may be more important. High exposure levels (L_{night} > 65 dB(A)) were excluded because in areas with very high exposures there is a relatively high risk of self-selection of persons not bothered by noise. The questions regarding sleep disturbance are given in Table 5.2. The scaling of the boundaries is based on the assumption that a set of categories divides the range from 0 (no sleep disturbance at all) to 100 (maximal sleep disturbance) in equally spaced intervals (see section 3.1).

Table 5.2: Datasets with the sleep disturbance question and response categories. The study codes in the first column refer to Fields' (2001) catalogue. If a dataset is not included in the overall exposure-response analyses (see text), the code is printed in italic. Cases are counted in the second column if valid noise exposure and sleep disturbance data are available. The last column gives key references.

AIRCRAFT			
Study	N	Sleep disturbance question	Reference
FRA-239	264	If aircraft noise wakes you up at night during weekday/weekend, how much does this annoy you? Not at all; a little; quite; very much.	Diamond,1986
NET-240	474	If aircraft noise wakes you up in the middle of the night during weekdays/weekends, how much are you annoyed? Not at all; a little; quite; very much.	Diamond,1986
UKD-024	2533	If noise heard ask: Do the aircraft ever wake you up? No; yes. If yes: When they wake you up how annoyed does this make you feel? Not at all; little; moderate; very.	Directorate of Operational Research and Analysis, 1967
UKD-238	598	If aircraft noise wakes you up in the middle of the night during weekdays/weekends, how much are you annoyed? Not at all; a little; quite; very much.	Diamond, 1986
UKD-242	1294	If noise heard ask: Do the aircraft ever wake you up? No; yes. If yes: If aircraft wake you up how annoyed does this make you feel? Very annoyed; moderately; a little ; not at all.	Brooker,1983
USA-022	1659	If aircraft heard or annoyed by aircraft : Now we need to know to what extent and how often you are disturbed by aircraft noise here in ... As I mention each activity, please tell me how much and how often you are bothered, using the Opinion Thermometer to select the appropriate: < activity=sleeping > Never; …; very often.	Hazard, 1971
NET-522	572	How often are you waken up by aircraft noise? (Nearly) every night; at least once a week; at least once a month; at least once a year; never.	Passchier-Vermeer, 2002

ROAD TRAFFIC			
Fields Code		Sleep disturbance question	Reference
CAN-120	938	I am often awakened by traffic noise in the middle of the night. Disagree very much;…;agree very much	Bradley, 1979
CAN-121	978	Does <SOURCE> interrupt sleeping? No; yes.	Hall, 1977
FRA-364	636	In a general manner, when you are at home during the night: very often you are waken up by traffic noise only. Disagree strongly; disagree; agree; agree strongly.	Vallet, 1996
GER-192	906	Please tell me using the scale, for every effect of road traffic noise, to which extent or how strong is it present? <effect=wakes up at night> Not; little; medium; reasonable; much.	Knall, 1983
GER-372	382	How often does road noise wake you up at night? Never; seldom; sometimes; often; very often.	Kastka, 1995
GER-373	247	How often does road noise wake you up at night ? Never; seldom; sometimes; often; very often.	Kastka, 1995
JPN-369	750	Does road traffic cause awakenings? No; yes a little annoyed; yes rather annoyed; yes very annoyed.	Yano, 1998
NET-106	392	Could you please tell me if you are disturbed by traffic noise when resting or sleeping? Never; seldom; sometimes; often.	Bitter, 1979
NET-258	240	Could you please tell me if you are disturbed by traffic noise when resting or sleeping? Never; seldom; sometimes; often.	De Jong, 1979
SWI-173	1116	Are there times when traffic noise disturbs your sleep? Almost daily; several times per week; sometimes; never.	Wehrli, 1978
TRK-367	118	Does road traffic noise you declared in "1b" disturb you while you are sleeping with the windows open/closed ? No; sometimes; yes	Kurra, 1995
UKD-072	404	When you are indoors at home, does road traffic ever wake you up? Yes; no.	Sando, 1975
FRA-524	551	The noise of road traffic wakes me up at night. Never; sometimes; often; always.	Cremezi, 2001
GER-523	801	Please tell me using the scale, for every effect of road traffic noise, to which extent or how strong is it present? <effect=wakes up at night> Not; little; medium; reasonable; much.	Griefahn, 1999

RAILWAYS			
Fields Code	N	Sleep disturbance question	Reference
GER-192	1020	Please tell me using the scale, for every effect of rail traffic noise, to which extent or how strong is it present? <effect=wakes up at night> Not; little; medium; reasonable; much.	Knall, 1983
JPN-370	375	Does rail traffic cause awakenings? No; yes a little annoyed; yes rather annoyed; yes very annoyed.	Yano, 1998
NET-153	387	Are you sometimes disturbed while resting or sleeping when the windows are open No; yes. If yes: If you have a window closed, how often are you disturbed when resting or sleeping? Never; seldom; sometimes; often.	De Jong, 1981
NET-276	200	Does the sound of a passing tram disturb you when resting, sleeping or going to sleep? Never; seldom; sometimes; often.	Miedema, 1988
UKD-116	773	Do trains ever wake you up? No; yes. If yes: When they wake you up how annoyed does this make you feel? Not at all; a little; moderate; very.	Fields, 1977
FRA-524	456	The noise of rail traffic wakes me up at night. Never; sometimes; often; always.	Cremezi, 2001
GER-523	887	Please tell me using the scale, for every effect of rail traffic noise, to which extent or how strong is it present? <effect=wakes up at night> Not; little; medium; reasonable; much.	Griefahn, 1999

For the studies USA-022, UKD-024, GER-372 and GER-373 L_{night} was not included in the dataset and could not be calculated or estimated on the basis of detailed information regarding the sites concerned. For these studies L_{night} has been estimated on the bases of data for periods other than 23-7h with general rules. These studies were excluded from the overall exposure-response analyses, but were used in analyses regarding the influence of additional variables. In those analyses L_{night} is less important than in the overall analyses that are the basis for relationships between self-reported sleep disturbance and L_{night}.

As shown by Table 5.2, there is a great variety of the wordings of the questions as well as the response alternatives. Many studies included more then one question regarding sleep disturbance. The questions can be divided in three broad categories on the basis of the particular type of disturbance by noise that was mentioned in the question: difficulty falling asleep due to noise, waking up or being disturbed by noise during the night, and waking up in the morning by noise earlier than planned. We used the most general questions that do not refer to either the beginning or the end of the night, i.e., the second category. These questions have been included in table 5.2. We excluded studies NET-106, NET-153, NET-258 and NET-276 with questions regarding disturbance of sleep or resting from all analyses, because resting is different from sleeping and need not take place only at night.

5.4 Relationships between exposure at the most exposed façade and self-reported sleep disturbance

As a first exploration of the relationship between L_{night} and self-reported sleep disturbance, the data for aircraft, road traffic, and railway noise have been analysed separately by fitting Equation 5.1 for each type of source, without including a study effect (see section 5.2). Table 5.3 gives the results. The estimated coefficient of L_{night} for aircraft is negative. Moreover, the estimated variance of the normal distribution of the sleep disturbance scores (s^2) is very (unusually) high (5690) for aircraft. Because of these outcomes for self-reported sleep disturbance caused by aircraft noise, no exposure–response relationships are presented for aircraft.

Table 5.3: Coefficients (b) of Equation 5.1 and their standard errors (s.e.), estimated for aircraft, road traffic, and railways separately. The dependent variable is self-reported sleep disturbance (see table 5.1). No study effect was included. Significance at the 5 % level is indicated with *, significance at the 1 % level with **. A lower value of –2L (-2 log likelihood) means a better model fit, but values from analyses with different numbers of cases cannot be compared directly.

	AIR		ROAD		RAIL	
	b	s.e.	b	s.e	b	s.e.
s^2	5690**	408	1710**	64	2530**	178
b_0	35.1*	17.8	-62.3**	5.7	-115.9**	13.2
L_{night}	-0.91**	0.34	1.29**	0.10	1.80**	0.23
-2L	6353		16057		5237	
N	3202		9016		3511	

In the following analyses of the road traffic and railway data, a common estimate was made of the individual variance (s^2) and a common estimate of the study variance (s_0^2). The first analysis allows for different intercepts and slopes for the road and rail by including dummy variable *Rail* and its product with L_{night} (*Rail* x *L*) in the model (Equation 5.2). As a consequence of including these dummy variables for rail, the intercept (b_0) and slope (coefficient of L_{night}) pertain to road traffic, while the coefficients of *Rail* and *Rail* x *L* give the 'adjustments' that must be applied to obtain the intercept and the slope for railway. The left part of table 5.4 gives the result. The coefficients of *Rail* and *Rail* x *L* are not significant, meaning that the intercept and the slope of the relationships of L_{night} and self-reported sleep for road traffic and for railway noise are not simultaneously significantly different.

Even though they are not significant at the 5 % level, the estimates of the coefficients of *Rail* and *Rail* x *L* are rather large from a practical point of view. This means that apparently the 'noise' in the data is so large that it is difficult to find possible meaningful differences between the two types of sources. Because a possible effect of the type of source may have been 'distributed' over *Rail* and *Rail* x *L*, the analysis has been repeated with only *Rail* and with only *Rail* x *L*. The results in table 5.4 show that then the effect of *Rail* x *L* is significant, while the effect of *Rail* is not. Thus it appears that there is a true difference in the level of sleep disturbance induced by road traffic noise and railway with the same L_{night}.

Table 5.4: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated on the basis of the combined road traffic and railway data allowing for different constants and slopes by including dummy *Rail* and its product with L_{night}. The dependent variable is self-reported sleep disturbance. No study effect was included. Significance at the 5 % level is indicated with *, significance at the 1 % level with **.

	Separate intercept & slope		Separate intercept only		Separate slope only	
	b	s.e.	b	s.e.	b	s.e.
s^2	1753**	58	1754**	58	1753**	58
s_0^2	287*	107	291*	110	287*	106
b_0	-86.0**	7.9	-82.8**	7.4	-86.8**	6.9
L_{night}	1.72**	0.11	1.66**	0.10	1.73**	0.10
Rail	-3.1	15.3	-17.1	9.1		
Rail x *L*	-0.25	0.22			-0.28*	0.13
-2L	20507		20508		20507	
N	12527					

Figure 5.1 shows the curves for three sleep disturbance measures *(%HSD*, *%SD,* and *%LSD*) and their 95% confidence intervals, together with the polynomial approximations of the curves, corresponding to the results in the right part of table 5.4. The curves are based on data in the L_{night} range 45-65 dB(A) (see section 5.3). The polynomial functions are close approximations of the curves in this range and their extrapolations to lower exposure (40-45 dB(A)) and higher exposure (65-70 dB(A)). The formulas of these polynomial approximations are for road traffic as follows:

$$\%HSD = 20.8 - 1.05L_{night} + 0.01486{L_{night}}^2$$

$$\%SD = 13.8 - 0.85L_{night} + 0.01670{L_{night}}^2$$

$$\%LSD = -8.4 + 0.16L_{night} + 0.01081{L_{night}}^2$$

and for railways:

$$\%HSD = 11.3 - 0.55L_{night} + 0.00759{L_{night}}^2$$

$$\%SD = 12.5 - 0.66L_{night} + 0.01121{L_{night}}^2$$

$$\%LSD = 4.7 - 0.31L_{night} + 0.01125{L_{night}}^2$$

The above relationships represent the currently best estimates of the influences of L_{night} on self-reported sleep disturbance for road traffic noise and for railway noise, when no other factors are taken into account.

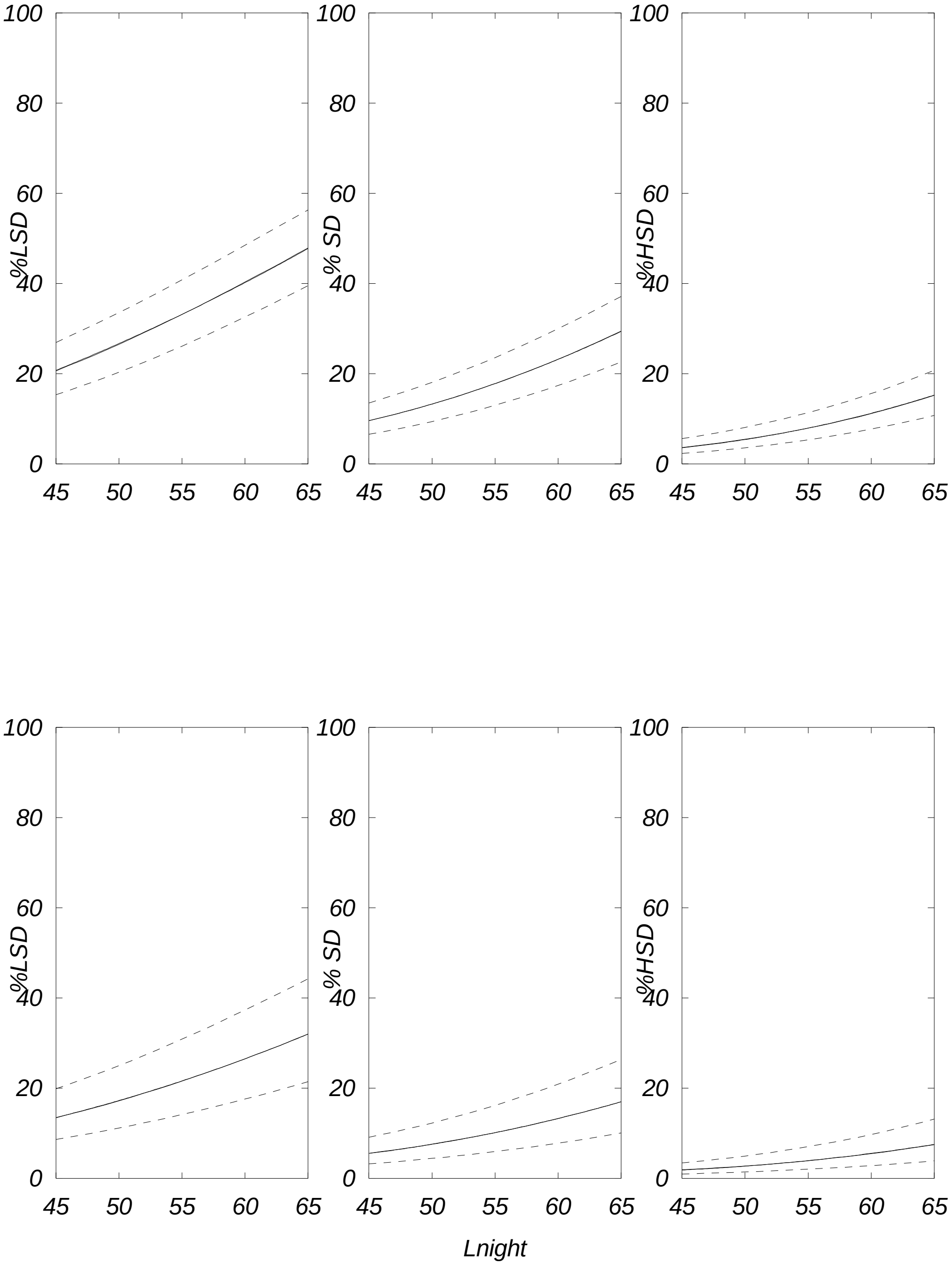

Figure 5.1: The relationships between L_{night} (outside at most exposed façade) and three sleep disturbance measures (*%HSD, %SD* and *%LSD*) (solid lines), their 95% confidence intervals (broken lines), and the polynomial approximations of the curves (coincide with original relationships) for road traffic (upper row) and railway (bottom row).

Table 5.5: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated on the basis of the combined road traffic and railways data, taking into account age. The dependent variable is self-reported sleep disturbance (see table 5.1). Significance at the 5 % level is indicated with *, significance at the 1 % level with **.

	b	s.e.
s^2	1746**	58
s_0^2	298**	112
b_0	-118.6**	8.2
L_{night}	1.74**	0.10
Rail x *L*	-0.28*	0.13
Age	138**	19
Age^2	-136**	20
-2L	20321	
N	12418	

The influence of age (note that the units are years/100) is investigated by including *Age* and Age^2 in Equation 5.2. The results in table 5.5 show that age has a curvilinear effect. At a given night-time exposure, self-reported sleep disturbance is maximal for persons of 51 years of age. This maximum is computed by equating the derivative of the curvilinear effect of age to zero and then solving for age. Then it is found that the equation for the maximal value of sleep disturbance at a given L_{night} (M) is: M = - (b_age / 2×b_age2), where b_age is the coefficient found for *Age* and b_age2 is the coefficient found for Age^2. Substituting in this equation the coefficient from table 5.5 gives 51 years as the age at which self-reported sleep disturbance is highest (with equal night-time exposure). Figure 5.2 illustrates the effect of age.

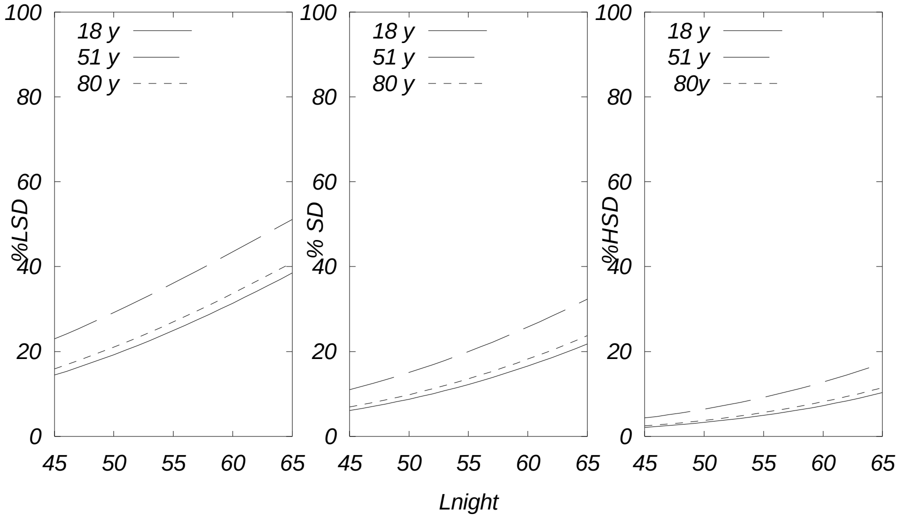

Figure 5.2: The relationships between L_{night} and three sleep disturbance measures *(%HSD, %SD* and *%LSD*) for three ages, for road traffic.

The role of several acoustical factors that may influence self-reported sleep disturbance in addition to L_{night} at the most exposed façade and age, is explored in the next sections.

5.5 Influence of difference in exposure between the most exposed and the bedroom façade

The difference between L_{night} at the most exposed façade and L_{night} at the façade of the bedroom of the respondent, *LDiff1*, has been assessed in two recent combined road traffic and railway noise studies. The French study FRA-524 assessed this difference for the whole sample, while in the German study GER-523 it has been assessed for a subset of the sample. Here, both studies were split into two datasets, one concerning road traffic noise exposure and self-reported sleep disturbance related to that noise, and the other concerning railway noise exposure and self-reported sleep disturbance related to railway noise. Table 5.6 gives the outcomes of the analyses of these four datasets in which *LDiff1* was included as independent variable. For three of the four datasets a weak, non-significant trend is found in the expected direction.

Table 5.6: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for individual datasets (studies), taking into account age and difference between most exposed façade and bedroom (*LDiff1*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **.

	ROAD				RAIL			
	FRA-524		GER-523		FRA-524		GER-523	
	b	s.e.	b	s.e.	b	s.e.	b	s.e.
s^2	1328**	213	1020**	199	1145**	167	2277**	723
b_0	-74**	30	-210**	50	-21	29	-446**	108
L_{night}	0.95**	0.39	1.88**	0.58	-0.22	0.39	4.65**	1.24
Age	92	79	631**	171	186**	77	911**	344
Age^2	-90	77	-720**	202	-174**	73	-1162**	443
Ldiff1	-0.15	0.27	-0.36	0.68	-0.07	0.25	-2.41	1.81
-2L	832		393		851		298	
N	551		164		456		210	

The four datasets have also been analysed in combination. In that analysis the level of the second source, *LSource2* (L_{night} at the most exposed façade of the second source), was also taken into account. Then still only a weak non-significant trend in the expected direction is found, and the coefficient of *LDiff1* is equal to -0.17 (s.e.: 0.16).

There are eight additional datasets which include information regarding the position of the bedroom of the respondent relative to the noise source. On the basis of this information two dummy variable, *Pos1* and *Pos2*, have been defined that are both equal to 0 if the bedroom is facing the noise source. *Pos1* is equal to 1 if the façade of the bedroom is more or less perpendicular to the road or railway, and *Pos2* is equal to 1 if the bedroom is facing more or less in the direction opposite to the noise source, or if there is no view on the source from the bedroom. The questions on which *Pos1* and *Pos2* are based, and the definition of *Pos1* and *Pos2* on the basis of the possible answers are given in table 5.7. Although the indication of the position of the bedroom relative to the source is not exact, table 5.8 shows significant, large effects on self-reported sleep disturbance.

Table 5.7: Datasets with a question regarding the position of the source relative to the bedroom or the visibility of the source from the bedroom, and response categories. Furthermore, the derivation of *Pos1* and *Pos2* from these data is described.

Study	Question	Definition of *Pos1* and *Pos2*
UKD-72	On which side of the house does the bedroom where you sleep look out(front [facing road], side,back)	if ‘front’ *Pos1*=0 and *Pos2*=0; if ‘side’ *Pos1*=1 and *Pos2*=0; if ‘back’ *Pos1*=0 and *Pos2*=1.
SWI-173	Which rooms in your apartment are directly facing the street, which are 90° to the street and which are completely away from the street. (living room, bedroom, children’s room, other [dining room, children, study], kitchen, bathroom, other). <bedroom>	Based on response regarding ‘bedroom’ if ‘directly facing’ *Pos1*=0 and *Pos2*=1; if ‘90°’ *Pos1*=1 and *Pos2*=0; if ‘completely away’ *Pos1*=0 and *Pos2*=1.
GER-192	From which room can you see the railway/street? (living room, bedroom)	Based on response regarding street for road traffic dataset, and response regarding railway for railway dataset. if bedroom was selected *Pos1*=0 and *Pos2*=0; if bedroom was not selected *Pos1*=0 and *Pos2*=1.
GER-372	What is the position of your bedroom in relation to the street? (towards the street, away from the street, perpendicular to street.	if ‘towards’ *Pos1*=0 and *Pos2*=0; if ‘perpendicular’ *Pos1*=1 and *Pos2*=0; if ‘away’ *Pos1*=0 and *Pos2*=1.
GER-373	Which rooms are facing the street or are away from the street? (bedroom, living room, kitchen, other)	if bedroom was selected *Pos1*=0 and *Pos2*=0; if bedroom was not selected *Pos1*=0 and *Pos2*=1.
GER-523	From which room can you see the railway/street? (living room, bedroom)	Based on response regarding street for road traffic dataset, and response regarding railway for railway dataset. if bedroom was selected *Pos1*=0 and *Pos2*=0; if bedroom was not selected *Pos1*=0 and *Pos2*=1

Table 5.8: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for individual datasets (studies), taking into account age and the position of the bedroom relative to the source concerned (*Pos1* and *Pos2*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **. A '-' indicates that a dichotomous sleep disturbance scale was used so that standard errors and significance levels could not be computed.

	ROAD												RAIL			
	UKD-072		SWI-173		GER-192		GER-372		GER-373		GER-523		GER-192		GER-523	
	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.
s^2	2499	-	564**	37	1177**	105	2078**	468	2497**	921	1568**	154	2493**	387	2381	369
b_0	-129	-	-81**	12	-159**	18	-23	51	-170**	70	-143**	25	-25	33	-248	42
L_{night}	2.06	-	1.49**	0.14	1.80**	0.23	-1.03*	0.57	2.73**	2.74	1.79**	0.30	0.32	0.49	2.91	0.53
Age	278	-	182**		341**		377**	165	8	215	278**	82	11	91	372	111
Age^2	-272	-	-165**		-316**		-370**	176	35	235	-274**	89	3	99	370	119
Pos1	-5.8	-	-9.4**	2.0	--		-26.0**	10.0	--		-	-	--		-	-
Pos2	-19.4	-	-22.1**	2.0	-17.8**	2.9	-26.1**	6.9	-26.3**	10.4	-16**	3	-33.7**	5.0	-23	5
-2L	504		2455		2005		681		293		1850		1549		1330	
N	403		1067		902		371		245		787		1004		878	

In order to get an overall estimate of the effect of sleeping at the relatively quiet side, the data have been analysed in combination. Then it is found that *Pos2* = - 20.1 (s.e.: 1.5). This reduction in self-reported sleep disturbance is relative to the disturbance found when the exposure at the most exposed side is equal, but the bedroom is not at the side opposite to the source (facing the source when *Pos1* is defined, and a mixture of facing and perpendicular when *Pos1* is not defined). Because the reference group is mixed, also including respondents with the bedroom façade perpendicular to the road or rail when *Pos1* is not defined, the actual benefit is larger than -20.1. Presumably due to the mixed reference group in this combined analysis, no effect is found of having the bedroom façade perpendicular to the road or rail.

The above results give a different indication regarding the role of sleeping at a quiet side of the dwelling. Based on the analyses with the actual difference in exposure of the most exposed façade and the façade of the bedroom, no significant benefit was found. However, a strong benefit of sleeping at the quiet side is found on the basis of analyses of the role of the bedroom position relative to the source. Further detailed analyses are required to find the (acoustical or non-acoustical) explanations of this apparent discrepancy.

5.6 Influence of insulation of the bedroom

The sound insulation of the bedroom of the respondent, *LIso*, has been assessed for a subsample of the German study GER-523. Table 5.9 gives the outcomes of the analyses in which *LIso* was included as independent variable. A trend in the expected direction (significant at the 10 % level) is found for road traffic, but not for railways.The absence of a significant insulation effect for railway may be related to the opening of windows at night.

The road traffic and railway datasets have also been analysed in combination, while allowing for different relationships with L_{night} for road and for rail. In that analysis the difference between L_{night} at the most exposed façade and at the façade of the bedroom, *LDiff1*, and the level of the second source, *LSource2*, were also taken into account. Then still only a non-significant trend in the expected direction is found. The coefficient of *LIso* is equal to –0.85 (s.e.: 0.44).

Table 5.9: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for the GER-523 road and rail datasets, taking into account age and insulation of the bedroom (*LIso*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **.

	ROAD		RAIL	
	b	s.e.	b	s.e.
s^2	1061**	212	2437**	817
b_0	-204**	51	-448**	142
L_{night}	2.08**	0.64	4.98**	1.86
Age	638**	178	822**	380
Age^2	-727**	210	-1051**	487
LIso	-0.81*	0.46	-0.20	0.78
-2L	372		227	
N	154		130	

There are six additional datasets with self-reported information regarding the type of windows in the bedroom. The type of window affects the insulation provided by the façade (when the windows are closed). On the basis of this information, one dummy variable, *Win*, has been defined. It is equal to 0 if the bedroom windows have single glazing, and it is equal to 1 if it has double glazing or other features that provide extra insulation. The questions on which *Win* is based, and the definition of *Win* on the basis of the possible answers, are given in table 5.10. The indications of the type of window are not exact. Table 5.11 shows no significant effects on self-reported sleep disturbance, except for road traffic in GER-192.

Table 5.10: Datasets included in the analyses in this paper, with the question regarding the type of windows in the bedroom, and response categories. Furthermore, the derivation of *Win* from these data is described.

Study	Question	Definition of *Win*
JPN-369	What type of windows does your bedroom have? (double glasses; single pane aluminium frame; single pane aluminium + wooden frame; single pane wooden frame; other)	if 'double glasses' *Win*=1, else *Win*=0 except 'other' then *Win*=missing
GER-192	Does your bedroom have; (Single glazing; Double windows with single glass; Double glazing)	if 'single glazing' *Win*=0, else *Win*=1
GER-372	What kind of windows do you have in your bedroom? (single; double for thermal insulation; double for noise reduction; triple; double windows=two windows behind each other).	if 'single glazing' *Win*=0, else *Win*=1
GER-373	What kind of windows do you have in your bedroom? (single; double for thermal insulation; double for noise reduction; triple)	if 'single glazing' *Win*=0, else *Win*=1
GER-523	Does your bedroom have: (single glazing; double glazing with single glass; or double glazing for thermal or noise insulation)	if 'single glazing' *Win*=0, else *Win*=1

Table 5.11: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for individual datasets (studies), taking into account age and the self-reported type of windows in the bedroom (*Win*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **.

	ROAD						RAIL					
	GER-192		JPN-369		GER-372		GER-373		GER-523		GER-192	
	b	s.e.	b	s.e.	B	s.e.	b	s.e.	b	s.e.	b	s.e.
s^2	1250**	112	2669**	471	2191**	469	2498**	830	1647**	167	2497**	347
b_0	-149.7**	18.6	-47.3	45.0	-25.7	51.2	-184.5**	68.1	-138.4**	26.6	-91.2**	30.9
L_{night}	1.54**	0.23	1.54**	0.56	-0.84	0.56	2.67**	0.95	1.75**	0.33	1.21**	0.46
Age	350**	61	-255*	141	317*	163	6	208	201**	85	3	90
Age^2	-327**	68	281*	147	-313*	174	33	229	-186**	93	11	98
Win	-6.6**	2.9	-0.3	13.3	10.2	8.7	5.1	11.5	5.4	6.2	6.4	4.9
-2L	2040		793		700		301		1761		1619	
N	903		690		375		247		741		1013	

In order to further study the role of the difference between outdoor and indoor noise level, the data from NET-522 have been used. In this study, the outdoor exposure to aircraft noise has been measured as well as the indoor exposure in the bedroom of the respondent during sleeping time. The difference between these two, *LDiff2*, reflects not only the insulation of the façade, but also the use of windows during the sleeping period. Table 5.12 shows that *LDiff2* has a significant effect on self-reported sleep disturbance.

Table 5.12: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for study NET-522, taking into account age and the difference between the outdoor level and the level in the bedroom caused by aircraft (*LDiff2*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **.

	NET-522	
	b	s.e.
s^2	1076**	135
b_0	-161**	60
L_{night}	3.33**	1.17
Age	222**	87
Age^2	-158*	92
LDiff2	-0.86*	0.44
-2L	828	
N	271	

5.7 Influence of exposure to an additional source

The night-time noise from a second source at the most exposed façade, *Lsource2*, has been assessed in ten datasets, including 4 aircraft noise studies. Table 5.13 gives the outcomes of the analyses in which *LSource2* was included as independent variable. In four of the ten datasets (one air, one road, two rail) a significant effect is found. Two of these datasets are parts of the same study. The effect of *LSource2* is positive in two datasets and negative in two other datasets. The direction of the effect of *Lsource2* is not the same for the two railway datasets. Thus, there appears to be no systematic effect of the noise level of a second source (at the most exposed façade) on the self-reported noise annoyance of a primary source.

Table 5.13: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for individual datasets (studies), taking into account age and the exposure to a second source (*Lsource2*). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **.

	AIR							
	UKD-238		FRA-239		NET-240		UKD-242	
	b	s.e.	b	s.e.	b	s.e.	b	s.e.
s^2	7686**	1720	744*	405	19111**	5826	6191**	1942
b_0	-351**	100	-99	89.68	-879**	229	-847**	306
L_{night}	3.88**	1.05	0.25	0.71	9.77**	2.93	8.26*	4.34
Age	136	285	138	215	1645**	594	1377**	396
Age^2	66	320	-87	236	-1754**	658	-1400**	407
Lsource2	0.40	0.67	0.39	0.86	-1.73	1.59	2.01*	1.13
-2L	773		113		601		307	
N	523		248		473		173	

	ROAD						RAIL					
	GER-192		FRA-524		GER-523		GER-192		FRA-524		GER-523	
	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.	b	s.e.
s^2	1357**	131	1266**	205	1671**	168	2167**	266	1066**	156	2150**	291
b_0	-128**	23	-99**	30.8	-127**	27	-65**	32	-82**	32	-261**	49
L_{night}	1.62**	0.26	0.60	0.38	1.90**	0.34	1.10**	0.43	0.44	0.39	3.32**	0.57
Age	227**	62	115	78	123	82	96	83	202**	75	243**	100
Age^2	-191**	69	-118	76	-102	90	-91	91	-183**	71	-236**	107
Lsource2	-0.12	0.15	0.73**	0.24	0.04	0.11	-0.63**	0.24	1.21**	0.27	0.08	0.34
-2L	2046		822		1881		1610		829		1358	
N	902		551		791		1012		456		883	

5.8 Influence of daytime noise

For most sources, night-time noise is strongly correlated with daytime noise. In order to find out whether the influence of daytime noise at the most exposed façade ($L_{07\text{-}23h}$) on self-reported sleep disturbance could be investigated, its correlation with L_{night} was calculated. Only for three studies ((UKD-242, UKD-072, and CAN-121) this correlation was sufficiently low (< 0.80) for inclusion of $L_{07\text{-}23h}$ as independent variable in addition to L_{night}. The results of the analyses with the daytime noise as additional independent variable are shown in table 5.14. The results indicate that L_{night} has a stronger and more consistent influence than $L_{07\text{-}23h}$. Thus, the limited evidence is consistent with the assumption that self-reported sleep disturbance reflects the night-time noise exposure (L_{night}) more than the daytime exposure ($L_{07\text{-}23h}$).

Table 5.14: Coefficients (b) of Equation 5.2 and their standard errors (s.e.), estimated for individual datasets (studies), taking into account age and daytime noise exposure ($L_{07\text{-}23h}$). The dependent variable is self-reported sleep disturbance. Significance at the 10 % level is indicated with *, significance at the 5 % level with **. A '-' indicates that a dichotomous sleep disturbance scale was used so that standard errors and significance levels could not be computed.

	AIR		ROAD			
	UKD-242		UKD-072		CAN-121	
	B	s.e.	B	s.e.	B	s.e.
s^2	8566**	1174	2498	-	2499	-
b_0	-323**	64	-160	-	-90	-
L_{night}	6.04**	0.94	1.16	-	3.46	-
Age	502**	118	287	-	-10	-
Age^2	-511**	122	-280	-	-3	-
$L_{07\text{-}23h}$	-2.18**	0.82	1.05	-	1.63	-
-2L	2147		509		818	
N	1284		404		936	

6 CONCLUSION AND DISCUSSION

Instantaneous effects

Sleep is a complex state that is altered when noise induces arousal. Arousal may lead to awakening, but often it has less pervasive consequences. Arousal involves neural and hormonal activity, and may be reflected in cardiovascular changes and motor activity (motility). Relationships have been presented that give the probability of (onset of) motility as a function of SEL^* or L_{max}^* in the bedroom for aircraft noise events. The probabilities pertain to the 15-s interval with the maximum noise level of the aircraft overflight. On the basis of the relationships for SEL^*, the expected yearly number of noise-induced motilities has been related to L_{night}, i.e. the yearly ‘average’ outdoor aircraft sound level between 23 – 7h. The total expected yearly number is at most:

$$\begin{aligned} n_{max} = \; & N \times [\, 0.0001233 \times (L_{night} + 70.2 - 10\lg N - LDiff1 - LDiff2)^2 \\ & - 0.007415 \times (L_{night} + 70.2 - 10\lg N - LDiff1 - LDiff2) \\ & + 0.0994]. \end{aligned}$$

where N is the number of aircraft noise events above the effect threshold (in terms of outdoor L_{max}: > 53 dB(A)). Furthermore, $LDiff1$ is the difference between L_{night} (at the most exposed façade) and the similar L_{Aeq} at the facade of the bedroom, $LDiff2$ is the actual difference between the night-time L_{Aeq} outdoors at the facade of the bedroom and in the bedroom during the sleep period. This difference takes into account the actual use of windows. Default values are $LDiff1 = 0$ dB(A) and $LDiff2 = 21$ dB(A).

For the derivation of the above relationships for n_{max}, the effects of the individual noise events are assumed to be independent, and a person is assumed to sleep each night precisely during the period from 23 to 7h. The ‘habituation’ of the instantaneous motility response that actually occurs at $L_{night} - LDiff1 - LDiff2 = 26$ dB(A) is assumed.

Chronic effects

The following relationship has been presented that gives the increase in mean motility, m_{night}, as a function of the outdoor L_{night} for aircraft noise events:

$$m_{night} = 0.000192 \times (L_{night} - LDiff1 - LDiff2).$$

Again, the default values $LDiff1 = 0$ dB(A) and $LDiff2 = 21$ dB(A) can be used.

The following relationships have been presented that give the percentage highly sleep disturbed (*%HSD*), sleep disturbed (*%SD*), and (at least) a little sleep disturbed (*%LSD*) by road traffic or railway noise as a function of the outdoor L_{night} at the most exposed facade for the source concerned. For road traffic:

$$\%HSD = 20.8 - 1.05 L_{night} + 0.01486 L_{night}^2$$

$$\%SD = 13.8 - 0.85 L_{night} + 0.01670 L_{night}^2$$

$$\%LSD = -8.4 + 0.16 L_{night} + 0.01081 L_{night}^2,$$

and for railways:

$$\%HSD = 11.3 - 0.55L_{night} + 0.00759L_{night}^2$$

$$\%SD = 12.5 - 0.66L_{night} + 0.01121L_{night}^2$$

$$\%LSD = 4.7 - 0.31L_{night} + 0.01125L_{night}^2.$$

No relationship could be assessed on the basis of the analysis of aircraft noise surveys, presumably because of different time patterns of night-time operations and insulation programmes related to aircraft noise in high exposure areas.

Long-term health effects
On the basis of mechanistic considerations it is plausible that, through instantaneous and chronic effects, night-time noise may increase the risk of (irreversible) cardiovascular disease. However, not many investigations regarding a direct link between night-time noise and cardiovascular disease have been conducted. There is recent evidence for a direct link with cardiovascular disease. However, currently there is not a sufficient basis for establishing exposure-response relationships for these types of effects.

The above relationships for motility and the default values are based on a recent, extensive field study in the Netherlands. Earlier studies give less detailed results, but do not contradict these results as far as comparisons could be made. Further verification of the above relationships is needed, and the applicability to sources other than aircraft need to be investigated. Furthermore, other default values may be appropriate for other noise sources, and for areas in Europe with other construction of dwellings, or other use of bedroom windows or air conditioning. In order to reflect improvements as a consequence of noise abatement measures, e.g. as a result of the implementation of noise action programmes, estimates of the actual values of especially *LDiff1* and possibly *LDiff2* may be used, instead of the defaults.

Instantaneous noise-induced motility has a curvilinear relation with age, with somewhat higher noise-induced effects for persons of 45 to 50 years compared the younger and older persons. There is a need to further explore the relationship between instantaneous motility and other aspects of noise-induced arousal (notably, awakenings and parameters of cardiovascular activity), and the relationship between mean motility and other chronic changes.
The above relationships for self-reported sleep disturbance are based on analyses of the 15 datasets with more than 12000 individual observations of exposure-response combinations, from 12 field studies. Self-reported noise-induced sleep disturbance has a curvilinear relation with age, with highest reaction found at circa 51 years. Further verification of the above relationships is needed with special attention for the role of *LDiff1* and *LDiff2*. The limited data concerning the effect of *LDiff1* showed no statistically significant effect, while the data regarding the effect of the position of the bedroom relative to the noise source show that the benefit of having the bedroom not facing the noise source is large.The limited evidence regarding the effect of insulation and *LDiff2* indicate that a reduction of the indoor bedroom sound level is more than 2 times less effective in reduction of self-reported sleep disturbance than the same reduction of the outdoor level. Analyses concerning the influence of night-time exposure to a second noise source and daytime noise from the source concerned indicated that reported sleep disturbance is

more strongly and consistently influenced by L_{night} from the source concerned than by the noise from a second source or daytime noise.

7 REFERENCES

Babisch, W., Fromme, H., Beyer, A., and Ising, H. Increased catecholamine levels in urine in subjects exposed to road traffic noise. The role of stress hormones in noise research. *Env Int*, 26: 475-481. 2001.

Basner, M., Buess, H., Luks, N., and Maass, H. Nachtfluglärmwirkungen - eine Teilauswertung von 64 Versuchspersonen in 832 Schlaflabornächten. Forschungsbericht 2001-26. 2001. Deutsches Zentrum für Luft- und Raumfahrt e.V.

Bitter, C. Perception and Experience of Traffic Noise in a Residential District along a State Highway. *Urban Ecology*, 4: 161-177. 1979.

Bonnet, M. H. Differentiating sleep continuity effects from sleep stage effects (Letter to the editor). *J Sleep Res*, 9: 403-406. 2001.

Borbeley, A. A., Neuhaus, H. U., Mattmann, P., and Waser, P. G. Langzeitregistrierung der Bewegungsaktivität: Anwendungen in Forschung und Klinik. Schweizer Medizinische Wochenschrift 1091(111), 730-735. 1981.

Born, J., Kern, W., Bieber, K., Fehm-Wolfsdorf, G., Schiebe, M., and Fehm, H. L. Night time plasma cortisol secretion is associated with specific sleep stages. *Biol Psychiatry*, 1415-1424. 1986.

Born, J. and Fehm, H. L. The Neuroendocrine Recovery Function of Sleep. *Noise & Health*, 7: 25-37. 2000.

Bradley, J. S. and Jonah, B. A. The Effects of Site Selected Variables on Human Responses to Traffic Noise, Part I: Type of Housing by Traffic Noise Level. *J Sound Vib*, 66: 589-604. 1979.

Brooker, P. Public Reaction to Aircraft Noise: Recent U.K. Studies. Proceedings of Internoise. 951-955. 1983.

Bullen, R., Hede, A., and Williams, T. Sleep disturbance due to environmental noise: a proposed assessment index. *Acoustics Australia*, 24: 91-96. 1996.

Carter, N. L. and Beh, H. C. The effect of intermittent noise on cardiovascular functioning during vigilance task performance. *Psychophysiology*, 26: 548-559. 1989.

Carter, N. L., Hunyor, S. N., Crawford, G., Kelly, D., and Smith, A. J. M. Environmental noise and sleep - A study of Arousals, Cardiac Arrhythmia and Urinary Catecholomines. *Sleep*, 17: 298-307. 1994.

Carter, N. L. and Inham, P. A laboratory study of the effects of background noise level and number of truck noise events on sleep. Report 124. 1995. Sydney National Acoustic Laboratories.

Carter, N. L. Some issues in noise-induced sleept disturbance. *Acoustics Australia*, 26: 49-52. 1998.

Cole, R. J., Kripke, D. F., Gruen, W., Mullaney, D. J., and Gillin, J. C. Automatic sleep/wake identification from wrist activity. *Sleep*, 15: 461-469. 1992.

Corcoran, D. W. J. Noise and loss of sleep. *Quarterly Journal of Experimental Psychology*, 14: 178-182. 1962.

Cremezi, C. and Lambert, J. Gêne ferroviaire de nuit Paris. Report Nos FC/DC/010514/3400. 2001. Paris, SNCF.

de Jong, R. G. A Dutch Study on Railway Traffic Noise. *J Sound Vib*, 66: 497-502. 1979.

de Jong, R. G. Beleving van Geluidwerende Voorzieningen Langs Rijksweg 10. *Geluid en Omgeving*, 4: 16-18. 1981.

Di Nisi, J., Muzet, A., and Libert, J. P. Cardiovascular responses to noise during sleeping and waking. Proceedings of the 6th International Congress on Noise as a Public Health Problem. 47-54. 1988. Stockholm.

Diamond, I. D. and Walker, J. G. An International Study of the Influence of Residual Noise on Community Disturbance to Aircraft Noise. Proceedings of internoise. 941-946. 1986.

Directorate of Operational Research and Analysis. Aircraft Noise in the Neighborhood of London Heathrow Airport, 1967. DORA Report no. 7105. 1971. London., Dept. of Trade and Industry.

Ericsz, W. J., Noordam, A., and Schoonderbeek, W. Trollificering van buslijn 9 in Arnhem. Onderzoek naar de effecten van geluidhinder. Noise series GA-HR-12-1. 1986. Leidschendam.

EU/WG2 - Dose/Effects. Position Paper on dose response relationships between transportation noise and annoyance. 2002.

Ficon. Review of Selected Airport Noise Analysis Issues. 1992. Washington, D.C., Federal Interagency Committee on Noise.

Fidell, S., Barber, D. S., and Schultz, Th. J. Updating a dosage-effect relationship for the prevalence of annoyance due to general transportation noise. *J Acoust Soc Am*, 89: 221-233. 1991.

Fidell, S., Hower, R., and Tabachnick, B. G. Noise-induced sleep disturbance in residences near two civil airports. NASA Contractor Report 198252. 1995. Hampton VA, NASA Langley Research Center.

Fidell, S., Pearsons, K., and Tabachnick, B. G. Field study of noise-induced sleep disturbance. *J Acoust Soc Am*, 98: 1025-1033. 1995.

Fidell, S., Hower, R., Tabachnick, B. G., Pearsons, K., Silvati, L., Sneddon, M., and Fletcher, E. Field studies of habituation to change in night-time aircraft noise and of sleep motility measurement methods. report no. 8195. 1998. Canoga Park, California, BBN Technologies.

Fidell, S., Pearsons, K., Tabachnick, B. G., and Hower, R. Effects of sleep disturbance of changes in aircraft noise near three airports. *J Acoust Soc Am*, 107: 2535-2547. 2000.

Fields, J. M. Railway Noise Annoyance in Residential Areas: Current Findings and Suggestions For Future Research. *J Sound Vib*, 51: 343-351. 1977.

Fields, J. M. An updated catalog of 521 Social Surveys of residents' reactions to environmental noise (1943-2000). NASA/CR-2001-211257. 2001. El Segundo, California, Wyle Laboratories.

Finegold, L. S., Harris, S., and von Gierke, H. E. Community Annoyance and Sleep Disturbance: Updated Criteria for Assessing the Impacts of General Transportation Noise on People. *Noise Control Eng.J.*, 42: 25-30. 1994.

Finegold, L. S. and Elias, B. A predictive model of noise induced awakenings from transportation noise sources. Proceedings of Internoise. -(on cd rom). Filename: in02_444.pdf. 2002. Dearborn (MI).

Flindell, I. H., Bullmore, A. J, and Robertson, K. A. Aircraft Noise and Sleep. 1999 UK Trial Methodology Study. Report 6131 R01. 2000. Southampton, ISVR.

Griefahn, B. Die Wirkung von Schiessgeräuschen auf die Herzfrequenz im Schlaf. *Z Lärmbekämpfung*, 36: 61-65. 1989.

Griefahn, B., Mehnert, P., Möhler, U., Schümer-Kohrs, A., and Schümer, R. A field study on the effects of railway noise and road traffic noise. Proceedings of Internoise. 2183-2188. 1996.

Griefahn, B., Möhler, U., and Schümer R.(Hrsg). Vergleichende Untersuchung über die Lärmwirkung bei Strassen- und Schienenverkehr (Hauptbericht-Textteil, Kurzfassung, Abbildungen und Tabellen,Dokumentationsanhang). 1999. München, SGS.

Guillemiault, C. and Stoohs, R. Arousal, increased respiratory efforts, blood pressure and obstructive sleep apnoea. *J Sleep Res*, 4: 117-124. 1995.

Hall, F. L. and Taylor, S. M. Predicting Community Response to Road Traffic Noise. *J Sound Vib*, 52: 387-399. 1977.

Harder, J., Maschke, C., and Ising, H. Längsschnittstudie zum Verlauf von Stressreaktionen unter Einfluss von nächtlichem Fluglärm. 1999. Berlin, Umweltbundesambt.

Hazard, W. R. Predictions of Noise Disturbance Near Large Airports. *J Sound Vib*, 15: 425-445. 1971.

Health Council of the Netherlands. Assessing noise exposure for public health purposes. Report 1997-23E. 1997. Rijswijk, Health Council.

Hofman, W. F. Vliegtuiglawaai, slaap en gezondheid. Achtergrondstudie in opdracht van de Gezondheidsraad. Report A91/1. 1991. Den Haag, Gezondheidsraad.

Horne, J. A., Pankhurst, F. L., Reyner, L. A., Hume, K. I., and Diamond, I. D. A field of sleep disturbance: effects of aircraft noise and other factors on 5.742 nights of actimetrically monitored sleep in a large subject sample. *Sleep*, 17: 146-159. 1994.

Inaba, R. and Okada, A. Study on the Effects of Infra- and Low Frequency Sound on the Sleep by EEG Recording. *Journal of Low Frequency Noise and Vibration*, 7: 15-19. 1988.

Ising, H. Stressreactionen und Gesundheitsrisiko bei Verkehrslärmbelastung. 1983. Berlin, Institut für Wasser-, Boden- und Lufthygiene des Bundesgesundheitsamtes.

Ising, H., Babisch, W., and Günther, T. Work noise as a risk factor in myocardial infarction. *J Clin Bas Cardiol*, 2-7. 1999.

ISO. Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment. ISO/FDIS 1996-1. 2002. Geneva, International Standards Organization.

ISO. Acoustics - Description, measurement and assessment of environmental noise - Part 2: Determination of environmental noise levels. ISO/CD 1996-2. 2002. Geneva, International Standards Organization.

Jurriëns, A. A., Griefahn, B., Kumar, A., Vallet, M., and Wilkinson, R. T. An essay in european research collaboration: common results from the project on traffic noise and sleep in the home. Proceedings of the 4th International Congress on Noise as a Public Health Problem. 2, 929-937. 1983. Torino.

Kastka, J., Borsch-Galetke, E, Guski, R., Krauth, J., Paulsen, R., Schümer, R., and Oliva, C. Longitudinal Study on Aircraft Noise Effect at Düsseldorf Airport 1981-1993. Proceedings of the 15th International Congress on Acoustics. 4, 447-451. 1995. Trondheim.

Knall, V. and Schümer, R. The Differing Annoyance Levels of Rail and Road Traffic Noise. *J Sound Vib*, 87: 321-326. 1983.

Kryter, K. D. Community annoyance from aircraft and ground vehicle noise. *J Acoust Soc Am*, 72: 1212-1242. 1982.

Kryter, K. D. Response of K.D. Kryter to modified comments by Th.J. Schultz on K.D. Kryter's paper "Community annoyance from aircraft and ground traffic noise". *J Acoust Soc Am*, 773: 1066-1068. 1982.

Kumar, A., Tulen, J. H. M., Hofman, W. F., van Diest, R., and Jurriëns, A. A. Does double-glazing reduce sleep disturbance during sleep? Proceedings of the 4th International Congress on Noise as a Public Health Problem. 2, 939-949. 1983. Torino.

Kurra, S., Tamer, N., and Rice, C. G. Environmental Noise Pollution Research Project Report. 1995. Istanbul, Technical University.

Maschke, C., Arndt, D., Ising, H., Laude, G., Thierfelder, W., and Contzen, S. Der Einfluß von Nachtfluglärm auf die "Streß"-Hormonausscheidung von Flughafenanwohnern. Forschungsbericht Nr.: Gr. 452/8-2, 1-127. 1994.

Maschke, C., Arndt, D., and Ising, H. Nächtlicher Fluglärm und Gesundheit: Ergebnisse von Labor- und Feldstudien. *Bundesgesundheidsblatt*, 38: 130-137. 1995.

Maschke, C., Arndt, D., Ising, H., Laude, G., Thierfelder, W., and Contzen, S. Nachtfluglärmwirkungen auf Anwohner. *Schriftenreihe des Vereins für Wasser-, Boden- und Lufthygiene*, 96: 1-140. 1995.

Maschke, C., Ising, H., and Hecht, K. Schlaf - nächtlicher Verkehrslärm - Streß - Gesundheit: Grundlagen und aktuelle Forschungsergebnisse. Teil II: Aktuelle Forschungsergebnisse. *Bundesgesundheidsblatt*, 3/97: 86-95. 1997.

Maschke, C., Wolf, U., and Leitmann, T. Epidemiological examinations to the influence of noise stress on the immune system and the emergence of arteriosclerosis. 2002. Berlin, Robert Koch-Institut.

Miedema, H. M. E. and Berg, R. Community Response to Tramway Noise. *J Sound Vib*, 120: 341-346. 1988.

Miedema, H. M. E. and Vos, H. Exposure-response relationships for transportation noise. *J Acoust Soc Am*, 104: 3432-3445. 1998.

Miedema, H. M. E. and Passchier-Vermeer, W. Beoordeling van geluidpieken in de woonomgeving. Report PG/VGZ/99.023. 1999. Leiden, TNO-PG.

Miedema, H. M. E. How does noise affect us? Proceedings of Internoise. 3-20. 2001. Den Haag.

Miedema, H. M. E. and Oudshoorn, G. C. M. Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals. *Environmental Health Perspectives*, 109: 409-416. 2001.

Möhler, U., Liepert, M., Schümer R.(Hrsg), and Griefahn, B. Differences between Railway and Road Traffic Noise. *J Sound Vib*, 231: 853-864. 2000.

Muzet, A. and Ehrhart, J. Amplitude des modifications cardiovasculairs provoquées par le bruit au cours du sommeil. *Coeur et Med Interne*, 17: 49-56. 1978.

Ollerhead, J. B., Jones, C. J., and Cadoux, R. E. Report of field study on aircraft noise and sleep disturbance. 1992. London, Civil Aviation Authority.

Öhrström, E., Rylander, R., and Björkman, M. Effects of night time road traffic noise - An overview of laboratory and field studies on noise dose and subjective sensitivity. *J Sound Vib*, 127: 441-448. 1988.

Öhrström, E., Agge, A., and Björkman, M. Sleep disturbances before and after reduction of road traffic noise. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International Congress on Noise as a Public Health Problem. 451-454. 1998. Sydney, University of Sydney.

Passchier-Vermeer, W. Noise and Health: review. Report nr A93/02E. 1993. Den Haag.

Passchier-Vermeer, W. Sleep disturbance due to nighttime aircraft noise. Report nr 94.077. 1994. Leiden.

Passchier-Vermeer, W., Steenbekkers, J. H. M., and Vos, H. Sleep disturbance and aircraft noise; questionnaire, locations and diaries. Report nr 2001.205. 2001. Leiden, TNO-PG.

Passchier-Vermeer, W., Steenbekkers, J. H. M., Waterreus, M. J. A. E., and Dam, P. J. C. M. Sleep disturbance and aircraft noise; tables, figures, pictures. Report nr 2001.206. 2001. Leiden, TNO-PG.

Passchier-Vermeer, W., Vos, H., Steenbekkers, J. H. M., van der Ploeg, F. D, and Groothuis-Oudshoorn, K. Sleep disturbance and aircraft noise. Exposure-effect relationships. Report nr 2002.027. 2002. Leiden, TNO-PG.

Passchier-Vermeer, W., Miedema, H. M. E., Vos, H., Steenbekkers, J. H. M., Houthuijs, D., and Reijneveld, S. A. Slaapverstoring en vliegtuiggeluid. TNO Report nr 2002.028, RIVM report nr 441520019, 2002. 2002. Delft, TNO-Inro.

Passchier-Vermeer, W. The relationship between the sound exposure level of a noise event and behavioural awakening. *(in preparation)*. 2003.

Patterson, S. M., Krantz, D. S., Montgomery, L. C., Deuster, P. A., Hedges, S. M., and Nebel, L. E. Automated physical activity and monitoring: validation and comparison with psychological and self-reported measures. *Psychophysiology*, 30: 296-305. 1993.

Pearsons, K., Bennett, R., and Fidell, S. Effects of cessation of late-night landings on behavioral awakening. Report nr 2439. 1973. Canoga Park, BNN Systems and Technologies Corporation.

Pearsons, K., Barber, D. S., and Tabachnick, B. G. Analysis of the predictability of noise-induced sleep disturbance. Report nr AD-A220. 1989. Canoga Park: BNN Systems and Technologies Corporation.

Pearsons, K. S., Barber, D. S., Tabachnick, B. G., and Fidell, S. Predicting noise-induced sleep disturbance. *J Acoust Soc Am*, 97: 331-338. 1995.

Reyner, L. A. Sleep disturbance and daytime sleepiness in normal subjects. 1995. Loughborough, Loughborough University of Technology.

Reyner, L. A. and Horne, J. A. Gender- and age-related differences in sleep determined by home-recorded sleep logs and actimetry from 400 adults. *Sleep*, 18: 127-134. 1995.

Sando, F. D. and Batty, V. Road Traffic and the Environment. *Social Trends*, 5: 64-69. 1975.

Schultz, Th. J. Synthesis of social surveys on noise annoyance. *J Acoust Soc Am*, 64: 377-405. 1978.

Smith, A. P. Noise, Neurotransmitters and Performance. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International Congress on Noise as a Public Health Problem. 1, 346-352. 1998. Sydney, University of Sydney.

Smith, A. P., Whitney, M., Thomas, K., and Brockman, P. Noise, Caffeine and Performance. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International Congress on Noise as a Public Health Problem. ı, 377-384. 1998. Sydney, University of Sydney.

Smith, A. P., Whitney, H., Owens, D., Sturgess, W., and Nutt, D. Noise, Central Noradrenaline and Lapses of Attention in a Categoric Search Task. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International Congress on Noise as a Public Health Problem. ı, 403-406. 1998. Sydney, University of Sydney.

Smith, A. P., Nutt, D., and Wilson, S. Noise and insomnia: a study of community noise, sleep disturbance, noise sensitivity and subjective reports of health. 2001. Cardiff, Centre for Occupational and Health Psychology, Cardiff University.

Thiessen, G. J. and Lapointe, A. C. Effects of continuous traffic noise on percentage of deep sleep, waking and sleep latency. *J Acoust Soc Am*, 73: 225-229. 1983.

TNO RIVM. Hinder, Slaapverstoring, Gezondeheid en Belevingsaspecten in de Regio Schiphol: Resultaten van een Vragenlijstonderzoek. TNO-PG Report nr 98.039 RIVM Report nr 441520010. 1998.

Vallet, M., Gagneux, J. M., and Simonnet, F. Effects of aircraft noise on sleep: an in situ experience. Proceedings of the 3rd international Congress on Noise as a Public Health Problem. ASHA Reports (no 10), 391-396. 1983.

Vallet, M., Gagneux, J. M., and Blanchet, V. Long term sleep disturbance due to traffic noise. *J Sound Vib*, 90: 173-191. 1983.

Vallet, M., Vernet, I., Champelovier, P., and Maurin, M. A road traffic Noise Index for the Night Time. Proceedings of Internoise. 2345-2350. 1996. Liverpool, England.

Vernet, M. Effects of train noise on sleep for people living in houses bordering the railway line. *J Sound Vib*, 66: 483-492. 1979.

Wehrli, B., Nemecek, J., Turrian, V., Hofmann, R., and Wanner, H. U. Auswirkungen des Strassenverkehrslärm in der Nacht. *Kämpf der Lärm*, 25: 138-149. 1978.

Whitehead, C., Hume, K. I., and Muzet, A. Cardiovascular responses to aircraft noise in sleeping subjects. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International Congress on Noise as a Public Health Problem. 471-474. 1998. Sydney, University of Sydney.

Wilkinson, R. T. and Campbell, K. B. Effects of traffic noise on quality of sleep: assessment by EEG, subjective report, or performance next day. *J Acoust Soc Am*, 75: 468-475. 1984.

Yano, T., Murakami, Y., Kawai, K., and Sato, T. Comparison of Responses to Road Traffic and Railway Noises. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International congress on noise as a public health problem. 2, 582-585. 1998. Sydney, University of Sydney.

Yano, T., Murakami, Y., Kawai, K., and Sato, T. Comparison of Responses to Road Traffic and Railway Noises. Carter, N. L. and Job, R. F. S. Proceedings of the 7th International congress on noise as a public health problem. 2, 582-585. 1998. Sydney, University of Sydney.

APPENDIX

Statement 1

Let f be a function of *SEL* that gives the expected number of instantaneous effects caused by a single event. With a given L_{night} and a given number of events *N*, the expected number of times that an effect occurs in the night, *n*, is maximal if all events have equal *SEL*, provided that $f\circ 10\lg$ is increasing but negatively accelerated.

Proof
By Jensen’s inequality,

$$(1/N)\ \Sigma_i\ f\circ 10\lg\,(10^{SELi/10}) \quad \leq \quad f\circ 10\lg\,(\ (1/N)\ \Sigma_i\ 10^{SELi/10}),$$

provided that the composite function $f\circ 10\lg$ is negatively accelerated increasing (concave). The summation runs over the *N* events. Using the definition of L_{night} in terms of *SEL* for rewriting the right hand side, rewriting gives

$$\Sigma_i\ f(SEL_i) \quad \leq \quad N \times f\,(L_{night} - 10\lg N + 70.2).$$

Since the left hand side $\Sigma_i\ f(SEL_i)$ is, by definition, the expected number of effects *n*, and the right hand side is the expected number of effects with given L_{night} and *N* events with equal *SEL*, this proofs the statement.

Statement 2

If

$$n_{max} \ = \ 10^{(Lnight-sel+70.2)/10}\ .\ f(sel),$$

has a maximum over *sel* and f is the quadratic function f(*SEL*) = a SEL^2 + b *SEL* + c, then the maximum occurs irrespective of L_{night} at

$$sel_0 \ = \ 4.34 - A \pm [(A - 4.34)^2 - (c/a) + 8.68A]^{½},$$

where A = b/(2a). (Only with + at the place of ± the value will come in the realistic range of *sel*)

proof
The value where n_{max} is maximal, sel_0, is found by setting its derivative over *sel* equal to 0. This gives

$$f'(SEL) \ - \ [(\ln 10)/10].f(SEL) \ = \ 0$$

where f’ is the derivative of f. Using that f(*SEL*) = a SEL^2 + b *SEL* + c so that f’(*SEL*) = 2a *SEL* + b, that (ln10)/10 = 0.23 and simplifying gives

$$a\,SEL^2 + (b - 2a/0.23)\,SEL + (c - b/0.23) \ = \ 0.$$

The solution of this equation is sel_0 as specified above.

Statement 3a

If the shape of the time pattern of the sound level has a block form, then $SEL = L_{max} + 10\lg T$, where L_{max} is the maximum sound level (integrated over 1-s) and T is the duration of the noise event in s.

proof
By defintion

$$SEL \quad = \quad 10\lg \int 10^{Lt/10}\,\mathrm{d}t$$

where the integration is over time T from the start to the end of the sound event. Because the pattern is a block form, $L_t = L_{max}$ so that

$$SEL \quad = \quad 10\lg\,(T \times 10^{Lmax/10}) \quad = \quad L_{max} + 10\lg T.$$

Statement 3b

If the sound level increases with rate a (in dB(A)/s) and after time point $t = 0$ decreases with rate $-a$, then $SEL \approx L_{max} - 10\lg a + 9.4$.

proof
By definition

$$SEL \quad = \quad 10\lg \int 10^{Lt/10}\,\mathrm{d}t$$

where the integration is over time from $-\infty$ to ∞. Because the sound level increases until $t = 0$ with constant rate a (in dB(A)/s) and thereafter decreases with constant rate $-a$, with integration from 0 to ∞,

$$SEL \quad = \quad 10\lg 2 \times \int 10^{(Lmax-at)/10}\,\mathrm{d}t \quad = \quad 10\lg\,[20/(a\ln 10) \times 10^{Lmax/10}\,].$$

Then simplifying gives the above result.