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Sleep and traffic noise
Summary report

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Contents

1 Introduction

1.1 Framework and aim of the study

This document presents a summary of the results of the field study ‘sleep and traffic noise’. The study was commissioned by the Netherlands Institute of Public Health and the Environment, financed by the Ministry of Housing, Spatial Planning and the Environment, and coordinated and conducted by TNO.

The aim of the project is to obtain information about:

1. relationships between *nighttime road traffic noise* and indicators of sleep disturbance, factors that affect these relationships and the extent of their effects
2. the extent to which indicators of sleep disturbance are affected by *intensive nighttime railway traffic* in comparison to exposure to nighttime road traffic noise
3. data that can be used to estimate prevalence of aspects of sleep disturbance in the Netherlands.

1.2 Locations and subjects

The field study took place between November 2004 and May 2005, at twelve residential quarters of cities and villages (‘locations’). Eight locations were situated in the vicinity of busy roads (‘road traffic locations’): three motorways, two urban access roads, and three main provincial roads. At the other four locations (‘railway traffic locations’) nighttime noise was mainly caused by railway traffic including freight trains.
Subjects were recruited by mail sent to each address at a location. In total 262 adult subjects participated in the study, living at about 7% of the addresses to which the invitation to participate was sent. Excluded from the study were: persons with nightshifts, people that used each night personal hearing protection, people that had to take medical care at night of members of the family, people that started using sleeping pills less than 6 weeks prior to the beginning of the study at a location.
Subjects participated six nights (1572 subject nights in total) and five days in the study: starting on Wednesday evening till Tuesday morning of the week thereafter. They were between 18 and 80 years old; 45% were men and 55% women. Over 30% of the subjects participated as the only one at an address, and nearly 70% of the subjects participated together with their partner. 210 of the 262 subjects resided at road traffic locations and the other 52 at railway locations. During participation in the field study subjects were exposed to road or railway traffic noise as usual for them.

1.3 Sleep and the measurement of indicators of sleep disturbance

Sleep is not only the absence of waking, but a cyclical, active physiological and hormonal process. By sleeping, human beings restore physically and mentally from their daytime activities. During sleep they also store and process information obtained during daytime. While asleep, often sympathetic activity decreases and parasympathetic activity increases. It is characterized by decreased sensory and motor functioning relative to the wake state. However, research has shown that sleeping human beings still react to sound: sound exposure decreases sleep depth, increases heart rate, and causes

an increase of (small) movements of the body (increase in motility). A more extreme reaction to sound is awakening.
To be able to carry out a field study about sleep disturbance on a large scale with a minimal intrusion on privacy and the sleep habits of subjects, actimeters have been used for the objective assessment of sleep disturbance. Subjects also filled out each evening and morning a diary with questions about daytime activities and aspects of their sleep, and registered each day on a card their sleepiness/tiredness at five points in time between 10 a.m. and 8 p.m. Before subjects participated in the study, they filled out an extensive questionnaire.
ECG measurements have been performed in a subgroup of 36 subjects (recordings during 172 subject nights). 22 subjects of the subgroup with ECG recordings resided at three road traffic locations (one motorway, one urban road, one provincial road) and 14 at the four railway traffic locations.

Actimeters are used to measure fine limb movements, usually of the wrist, which are indicative of sleep disturbance. They are small devices worn like a wristwatch and easily used in the home without supervision. They log and store data for many days and nights, which is later transferred to a computer for analysis. In the present study actimeters (Cambridge Neurotechnology Ltd, UK, type AW4) stored in their internal memory, at the end of subsequent 15-s intervals, time and information from which it can be deduced whether or not a (small) movement (motility) has occurred during that interval. Our subjects slept on average 7,5 hours per night. During those 1800 15-s intervals on average 100 intervals with motility were recorded. This corresponds to an overall probability of 0.054 of recording an interval with *motility*. For comparison, during physical exercise while awake the probability of motility nearly equals 1. In somewhat over 50 15-s intervals motility starts to occur during sleep: overall probability of *motility onset* during sleep is 0.030. The actimeter is equipped with a marker, which allows the subject to register when he or she is awake during the sleep period (self-registered awakening).

1.4 Noise measurements

To measure nighttime noise one outdoor noise monitor (Larson & Davis, model 870) and 12 indoor noise monitors (Larson & Davis, model 820) were used. The outdoor noise monitor was located in the vicinity of the busy road or railway on private terrain (garden or balcony of a subject). The location of the outdoor noise monitor could not be fully standardized, because the choice of the location of the monitor was not only based on acoustical requirements, but also on the need of a nearby power supply and the need to minimize the possibility of vandalism. Each noise monitor continuously recorded the *A-weighted 1-s sound level* between 22:00 and 9:00 hours during each study night[1]. From the average of the differences between the *outdoor maximum sound levels* and the *indoor maximum sound levels* of the loudest traffic noise events in the quietest part of the nights for each bedroom the so-called *outdoor-indoor-difference* (*oid*) has been calculated. An *indoor traffic noise metric* has been assessed by subtracting *oid* from an

[1] Basic noise metrics (maximum sound level, sound exposure level (SEL), equivalent sound level over a period T) have been used according to the definitions given in:
ISO. Acoustics - Description, measurement and assessment of environmental noise
- Part 1: Basic quantities and assessment. Geneva: International Standards Organization; 2003; ISO 1996-1
- Part 2: Determination of environmental noise levels (Draft). Geneva: International Standards Organization; 2006; ISO/FDIS 1996-2.

outdoor traffic noise metric. On the basis of the *indoor noise measurements* we calculated *indoor noise exposure due to any noise* in the bedroom during sleep.

From the *A-weighted 1-s sound levels* measured outdoors and the sleep periods of subjects, for each location the mean value (averaged over subjects at a location) of the *equivalent sound level outdoors during the sleep of subjects* has been calculated. These mean values ranged from 49 to 65 dB(A). Also, for each location the mean value (averaged over subjects at a location) of the *equivalent sound level indoors due to traffic noise during the sleep of subjects* has been assessed. These mean values are about 25 dB(A). Differences between mean outdoor and indoor values (mean 'sound attenuation') are, among other things a result of the sound insulation of the bedroom, the position of the bedroom relative to the noise source (with or without a view on the road or railroad), and the position of the bedroom window (window closed or opened).

From the *A-weighted 1-s sound levels* measured outdoors between 23:00 and 7:00 hours we calculated for each location a quantity *p40db*, the percentage of time the *A-weighted 1-s sound level* did not exceed 40 dB(A). In the present investigation *p40db* of motorway traffic is about 1,5%, of railway traffic about 40% and of urban/provincial road traffic between 5 and 50%. The (nearly) complete absence of low background at the motorways and some urban and provincial roads is due to the large number of passing vehicles at these locations, noise from traffic at distant and traffic sound reflected by objects in the surrounding (dwellings and trees at a distance, also at the other side of the road). This leads to a 'blanket' of (low frequency) noise along motorways that appears at the motorway locations in the study to be practically independent of the distance to the road.

We also calculated the quantity *L90,8h*, the level exceeded by 90% of the *A-weighted 1-s sound levels* measured outdoors between 23:00 and 7:00 hours (on average for motorway locations *L90,8h* is 45 dB(A), for locations with urban/provincial road traffic about 38 dB(A), for railway locations 35 dB(A)). The correlation between the logarithm of *p40db* and *L90,8h* is very high (correlation coefficient equal to –0.97).

1.5 Questionnaire to persons that did not participate in the field study

To assess whether the results of the study are affected by selective response of subjects, we requested non-participating persons living at addresses originally approached, adjacent to the addresses of the participating subjects, to fill out a questionnaire immediately after the field study was ended at that location. In total 183 persons filled out the non-response questionnaire. The answers did not provide an indication of bias by selective response of the participating subjects.

2 Exposure-effect relationships

2.1 Introduction

Data have been analyzed on three time-scales:

- Instantaneous level: we related *effect variables assessed in 15-s intervals* [probability of motility, probability of motility onset, probability of self-registered awakening, average heart rate, average Inter Beat Interval (IBI), and variability in IBI (assessed for each heartbeat over a period of five minutes, from 2.5 minutes before until 2.5 minutes after the heartbeat)] to *variables of the noise exposure during a vehicle passage* or variables of other noise exposures in the bedroom on a similar time-scale
- On a 24-hours level (including one sleep period and one sleep latency period): we related *indicators of sleep disturbance representative of one sleep period* to *traffic noise exposure during one sleep period* or exposure to all or to other noises in the bedroom on the same time-scale; we also related *indicators of sleep disturbance representative of one sleep latency period* to *traffic noise exposure during such a period*
- On an aggregated level or a long-term level: we related *indicators of sleep disturbance aggregated over six sleep periods* and *indicators of sleep disturbance obtained by questionnaire* (and representative of a longer period) to *nighttime traffic noise exposure during six sleep periods* or noise exposure in the bedroom on the same time-scale.

The analyses performed are summarized in the following table:

	event	*night*	*aggregated, long-term*
motility	+	+	+
self-registered awakening	+	+	+
heartbeat	+	+	+
diary/sleepiness card	n.a.	+	n.a.
questionnaire	n.a.	n.a.	+

The first column lists the relevant effect variables: motility, self-registered awakening, heartbeat variables, variables obtained from the diaries and the daytime sleepiness cards, and variables from the questionnaire. A + in the three following columns indicates that analyses have been performed with the effect variables on the indicated time-scale and ‘n.a.’ that such analyses are not applicable.

Below, the results of the analyses with respect to exposure-effect relationships are given, and where relevant results are discussed per section. Summaries are given in small tables using the same effect variables as in the former table. The following symbols have been used in these small tables:

- ++ one or more effect variables have a strong (statistically significant) relationship with *noise exposure indoors due to traffic noise*
- + at least one effect variable has a (statistically significant but relatively weak) relationship with *noise exposure indoors due to traffic noise*
- –/+ none of the effect variables have a (statistically significant) relationship with *traffic noise exposure indoors* and one or more effect variables have a (statistically significant) relationship with *noise exposure indoors due to any noise*

- – none of effect variables have a (statistically significant) relationship with *any noise exposure indoors*, or the relationship was not in accordance with the hypothesis formulated before the analyses
- n.a. not applicable.

Exposure-effect relationships have been assessed by performing multi-level (logistic) multi-variate regression analyses with subjects as random factor. On the basis of hypotheses formulated before analyses, relationships have been tested one-sided at a level of significance of 0.05.

On each of the three time-scales, we did not find any relationships between *traffic noise exposure measured outdoors at one specific place per location* and effect variables.

2.2 Acute effects

2.2.1 Introduction

	event
mot	++
awak	-
heart	-/+
diary	n.a.
quest	n.a.

The period of analysis for acute effects of traffic noise events was limited to 0:00 to 4:00 hours in case of nights preceding workdays (Sunday through Thursday night) and to between 1:00 and 5:00 hours in case of nights preceding weekend days (Friday and Saturday night). This implies that effects during only a part of the sleep period have been considered. Only in 10% of the nights a sleep period after 4.5 hours of sleep was included in the analyses, since in 10% of the subjects nights subjects fell asleep before 23:30 hours on nights before weekdays or before 0:30 hours for nights before weekend days.

A traffic noise event has been defined on the basis of the *outdoor* noise measurements. We first specified the (usually small) intervals during which the 1-s sound levels exceeded *L90,30min* by at least 15 dB(A) (*L90,30min* is the sound level that is exceeded by 90% of the *1-s sound levels* during a 30 minutes period). Then we assessed the *maximum sound level* during such an interval. If we could establish within such an interval a – 10 dB(A) point (*1-s sound level* that does not exceed the *maximum sound level* minus 10 dB(A)) before and one after the *maximum sound level* we concluded to the presence of a traffic noise event loud enough to be distinguished from the background. In this way traffic noise events of passing trains and vehicles on urban and provincial roads were considered as such if they had an *outdoor maximum sound level* of at least 58 dB(A) and vehicles on motorways if they had an outdoor *maximum sound level* of at least 65 dB(A). In total nearly 6300 traffic noise events were included in the analyses.

To analyze acute effects on motility, heart rate and self-registered awakening by traffic noise events the so-called *effect evaluation interval* was introduced. We added to the 15-s interval(s) during which a traffic noise event was detected on the outdoor noise monitor two 15-s intervals: one 15-s interval before the (first) 15-s interval of a traffic noise event and one 15-s interval after the (last) 15-s interval with traffic noise. This was deemed necessary as it turned out to be not possible to determine with sufficient accuracy the time that vehicle passes the bedroom of a subject from the time a vehicle passes the outdoor noise monitor. The analyses comprised in total more than 48000 effect evaluation intervals of subjects. They have an average duration of 4.4 15-s intervals, over 70% of the effect evaluation intervals consist of 3 or 4 15-s intervals, and 2.5% of the effect evaluation intervals of the railway noise events last at least 2 minutes.

Acute effects of traffic noise exposure were established from the differences in effect variables at 15-s intervals within and outside effect evaluation intervals. They were related to the time after sleep onset and to a noise exposure metric. If an effect variable is a binary quantity (such as motility or self-reported awakening), the effect is described by the noise-induced probability of the effect in a 15-s interval.

The instantaneous noise metrics that were shown to be related to effect variables are the *maximum sound level outdoors* of a traffic noise event minus *oid* (*Lmax_oid*), *SEL* of a traffic noise event minus *oid* (*SEL_oid*), and *SEL* indoors during a 15-s interval of an effect evaluation interval (*SEL_indoors*). *SEL_indoors* during a 15-s interval of an effect evaluation interval has been calculated from the total SEL indoors during that effect evaluation interval by taking into account the number of 15-s intervals during that interval[2].

2.2.2 Motility

	event
mot	++
awak	-
heart	-/+

1. Results for 15-s intervals

Relationships have been examined between probability of motility and of motility onset in 15-s intervals and each of the three instantaneous noise metrics mentioned above. Each of the six relationships has a statistically significant noise metric coefficient: noise-induced probability of motility and noise-induced probability of motility onset increase with *Lmax_oid*, *SEL_oid*, and *SEL_indoors*. Noise-induced probability of motility and of motility onset are less strongly related to *Lmax_oid* than to *SEL_oid*. For *SEL_indoors* the relationships are somewhat stronger than for *SEL_oid*.

Time after sleep onset is an important determinant of the relationships: noise-induced probability of motility and of motility onset due to the loudest traffic noise events found in the study are about a factor five larger 4.5 hours after sleep onset than 0.5 hours after sleep onset. Noise-induced probability of motility in a 15-s interval due to the loudest traffic noise events is 10 to 15% of overall probability of motility (0.054) at 4.5 hours after sleep onset; at that point in time noise-induced motility onset is about 10% of overall probability of motility onset (0.030).

In the relationships the background noise variable *p40db* is also a determinant. Noise-induced probability of motility in a 15-s interval due to the loudest traffic noise events at 4.5 hours after sleep onset is for *p40db* equal to 1.5% (motorways) about 25% larger than for *p40db* equal to 40% (railway traffic); for noise-induced motility onset this difference is smaller: about 10% instead of 25%.

At equal values of a noise metric, noise-induced probability of *motility onset* in a 15-s interval is larger in men than in women. For instance, it is for the loudest traffic noise events at 4.5 hours after sleep onset about 1.5 times larger in men than in women; in this case the difference between men and women is about 4.5% of overall motility onset (0.030). There appeared to be no difference between men and women in noise-induced probability of *motility*. This implies that motility onset due to traffic noise and due to all noises in the bedroom occurs somewhat more often in men, but that the periods of motility are of somewhat shorter duration in men than in women.

The type of noise source (motorway traffic, urban/provincial road traffic, railway traffic) does not affect the outcome of our analysis. Differences observed for different noise sources can be explained by differences in *p40db*.

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2 For instance, if a total indoor SEL of 50 dB(A) was obtained for an effect evaluation interval of 4 15-s intervals, then SEL_indoors of each of these 15-s intervals was taken as 50 – 10*log 4 = 44 dB(A).

2. Motility by traffic noise events

From the noise-induced probability of motility and of motility onset *during a 15-s interval*, noise-induced probability of motility and of motility onset *due to traffic noise events* were estimated by taking into account the number of 15-s intervals in the effect evaluation intervals. In general, the probability of noise-induced *motility* during an effect evaluation interval of average duration is about 3.5 times the value during a 15-s interval of such an effect evaluation interval. For *motility onset* it is about a factor 3.8. For railway noise events with an effect evaluation interval of at least 2 minutes, the probability of motility and of motility onset are about 1.5 times the values for noise events with an average effect evaluation interval. Therefore, the probability of noise-induced *motility* due to the loudest noise events of average duration at 4.5 hours after sleep onset is about 50% of the overall probability of motility (probability of motility increases from 0.054 to 0.081) and the probability of noise-induced *motility onset* about 40% of the overall probability of motility onset (probability of motility onset increases from 0.030 to 0.042).

3. Comparison of motility due to road and railway traffic noise events with motility due to aircraft noise events

The exposure-effect relationships obtained in the present study with respect to noise-induced motility and motility onset due to traffic noise events have been compared with the relationships obtained in our earlier investigation on aircraft noise in the vicinity of Amsterdam Airport Schiphol[3]. Noise-induced probability of motility due to traffic noise events of average duration at about 4 hours after sleep onset is observed at a lower value of *Lmax_oid* than for aircraft noise events. However, at *Lmax_oid* equal to 45 dB(A) (the value exceeded in 10% of the traffic noise events) the noise-induced probability of motility due to traffic noise events is about 40% of the value due to aircraft noise events (at about 4 hours after sleep onset). For noise-induced motility onset this percentage is about 50%.

The 2.5% railway noise events with effect evaluation intervals of at least 2 minutes have at *Lmax_oid* equal to 45 dB(A) effects on motility and motility onset that are of the same order of magnitude as aircraft noise events at the same *Lmax_oid*. However, exposure-effect relationships for aircraft noise events could be specified up to *Lmax_oid* of 68 dB(A) (the value found to be exceeded in 10% of the aircraft noise events). At that value the probability of aircraft noise-induced motility and of motility onset is about four times larger than at 45 dB(A). So, at about the same time after sleep onset, the loudest aircraft noise events found increase the probability of motility and motility onset to a much larger extent (by about a factor 4) than the loudest and longest railway traffic noise events found in the present study.

4. Factors with an effect on instantaneous relationships

Besides the additional variables we already mentioned (time after sleep onset, gender and *p40db*) we did not find any other factors with an effect on the relationships for probability of motility and of motility onset. Our earlier investigation on aircraft noise showed that the total aircraft noise exposure, aggregated over all sleep periods of a subject, was an important additional factor: with increasing total aircraft noise exposure the acute effects on probability of motility decreased. We did not find such an effect in our present investigation.

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[3] Passchier-Vermeer W, Vos H, Steenbekkers JHM, van der Ploeg FD, Groothuis-Oudshoorn K. Sleep disturbance and aircraft noise. Exposure-effect relationships. Leiden: TNO-PG; 2002; Report nr 2002.027.

2.2.3 Self-registered awakening

	event
mot	++
awak	-
heart	-/+

The percentage 15-s intervals in which subjects pressed the marker on the actimeter to indicate that they were awake, is somewhat higher inside than outside effect evaluation intervals (0.082 versus 0.077; for a sleep period of average duration 0.082% implies on average 1.5 and 0.077 1.4 self-registered awakenings). The difference is not statistically significant. The difference in percentage 15-s intervals with self-registered awakenings between men and women is statistically significant (0.068 versus 0.086; on average for a sleep period 1.2 versus 1.6 times self-registered awakening).

2.2.4 Variables of heartbeat

	event
mot	++
awak	-
heart	-/+

The heartbeat variables studies are average heart rate, average IBI and average variability in IBI over 15 seconds, maximum heart rate and minimum IBI in 15-s intervals. The latter two were chosen since from earlier experiments reported in the literature it appeared that heart rate might increase (and IBI decrease) for a short period of time (in the order of seconds) as a first acute reaction to noise exposure. This leads to the hypothesis that exposure to traffic noise induces a higher maximum in heart rate (and minimum in IBI) within the effect evaluation intervals than outside these intervals.

Only relationships with *SEL_indoors* as noise exposure metric have been found. Time after sleep onset affects these relationships. The heart rate of male subjects is hardly influenced by bedroom noises. At *SEL_indoors* at a 15-s interval equal to 55 dB(A) (the level exceeded in 10% of the values of *SEL_indoors*) male subjects show at 4.5 hours after sleep onset an increase in maximum and average heart rate and decrease in minimum IBI and average IBI of 0,5 – 1% of the overall values for males. Female subjects do show more acute reactions. At *SEL_indoors* at a 15-s interval of 35 dB(A) (the level not exceeded in 10% of the values of *SEL_indoors*) the increase in average and maximum heart rate is about 1.5 beats per minute (2% of the overall average for women) and at the highest noise exposures (*SEL_indoors* in a 15-s interval equal to 55 dB(A)) these increases are up to 2.5 beats per minute (3.5% of the overall average for women).

2.2.5 Limitations

Our analyses showed that acute effects increase to a large extent in the course of the sleep period. Since we analyzed these effects only in the first hours of the sleep periods, up to 4.5 hours (which corresponds to 60% of an average sleep period), we are not able to specify relationships that relate to the period after 4.5 hours after sleep onset. However, we expect larger effects than effects presented in this document for the first 60% of the sleep period.

2.3 Effects during a part of a 24-hours period

2.3.1 Introduction

	night
mot	++
awak	++
heart	+
diary	-/+

The following parts of a 24 hours period have been considered:

- sleep period
- sleep latency period (period between time of falling asleep and time of trying to go to sleep)
- day and evening after a sleep period.

Noise exposure for the analysis of 24-hours time periods has been characterized by:

- *Equivalent sound level measured outdoors during a sleep period* of a subject minus *oid*, denoted by ‘indoor traffic noise exposure’
- *Equivalent sound level measured indoors during a sleep period* of a subject, denoted by ‘total indoor noise exposure’
- The (exponential) difference between the total indoor noise exposure and indoor traffic noise exposure, denoted by ‘non-traffic related indoor noise exposure’.

Traffic noise exposure during the sleep latency period has been characterized by the *equivalent sound level measured outdoors* during that period minus *iod*, and total indoor noise exposure during sleep latency period by the *equivalent sound level measured indoors* during that period.

2.3.2 *Effects during sleep periods*

Motility

1. Motility in the present study

	night
mot	++
awak	++
heart	+
diary	-/+

Mean motility and mean motility onset depend on *indoor traffic noise exposure* in males, but not in female subjects. Mean motility and mean motility onset of both men and women depend on *total indoor noise exposure*. The background level, characterized by *p40db*, is a factor affecting the relationships of mean motility and mean motility onset with both *indoor traffic noise exposure* and *total indoor noise exposure*. Related to their low background noise levels, the mean motility and the mean motility onset of men and women at railway traffic locations are lower (about 28% of the overall values) than those of men and women near motorways at the same level of *indoor traffic noise exposure*. The mean motility and mean motility onset of men and women at urban/provincial traffic locations are about 18% of the overall values lower than those of men and women near motorways at the same *indoor traffic noise exposure*.

Although the analysis showed that motility in women is not affected by traffic noises during sleep, other, non-traffic related, noises have about the same effect in women as in men.

We further analyzed the relationship between *motility* and *indoor traffic noise exposure* for the influence of other variables. *Indoor noise exposure caused by non-traffic related noises* is a confounder, which explains for 38% the increase in motility in men due to *indoor traffic noise exposure*. Of all other possible variables (including age) only ‘use of personal hearing protection’ and ‘use of sleeping pills or sleep inducing drugs’ turned out to have an effect. Their effect on the relationship between motility and *indoor traffic noise exposure* is relatively small.

2. Including data from reference locations

The present investigation did not include locations with only minor nighttime traffic noise. To obtain information about subjects with hardly any traffic noise exposure at night we used effect data (with respect to average motility during sleep) from our field study on aircraft noise, performed three years earlier in the vicinity of Amsterdam Airport Schiphol (Passchier-Vermeer et all.[4]). Procedures, motility measurements, and noise measurements in both field investigations are similar. We selected from that study the two reference locations, with practically no nighttime aircraft, road and railway

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[4] Passchier-Vermeer W, Vos H, Steenbekkers JHM, van der Ploeg FD, Groothuis-Oudshoorn K. Sleep disturbance and aircraft noise. Exposure-effect relationships. Leiden: TNO-PG; 2002; Report nr 2002.027.

traffic. These locations with *p40db* equal to 57% and *L90,9h* equal to 32 dB(A) have (much) lower backgrounds at night than the locations in the present field study.
The relationships obtained by including data obtained from these are essentially the same as those without these data.

3. Comparison with other data sets
The finding that motility and motility onset during sleep at locations where low background sound levels are absent (near motorways) is much higher than at locations where low background levels are present (near railways and some urban and provincial roads) has been observed for the first time in this study. To try to confirm this observation, the original data from two other data sets have been analyzed and results have been compared with those of the present study. It concerns:

a. the full data set from our field study on aircraft noise, performed three years earlier in the vicinity of Amsterdam Airport Schiphol. The study comprised 418 subjects (4598 subjects nights), with 360 subjects exposed to aircraft noise and 58 subjects at reference locations
b. data from a large German field investigation on sleep disturbance caused by road and railway traffic noise (Griefahn et all, 1999, Möhler et all, 2000[5]). The study comprised 188 subjects (1710 subject nights) exposed to road traffic noise and 188 subjects (1581 subject nights) exposed to railway traffic noise. Subjects at railway traffic locations were exposed to traffic noise at an on average 5 dB(A) higher *outdoor nighttime traffic noise equivalent sound level over eight hours* than subjects at road traffic locations.

Ad a. Comparison with the aircraft sleep disturbance study
For each of the 15 locations (including the two reference locations) *p40db* has been obtained from the *1-s sound levels* on the outdoor noise monitor. The average value of *p40db* appeared to be 40%, with only three locations with *p40db* less than 30%. The distributions of the outdoor 1-s sound levels are similar to those at the railway traffic locations in the present investigation. Relationships have been assessed with indoor traffic noise exposure as noise metric and average motility during the sleep period as effect variable, and *p40db* as possible additional factor. It turned out that *p40db* was not of importance in the relationship. This is not surprising, since locations with low values of *p40db* (high background levels) in the study are lacking. In general, the increase of motility with indoor aircraft noise exposure turned out to be about the same as this increase with indoor road and railway traffic exposure found in the present study, although details of the relationships with respect to age and gender differed.

Ad b. Comparison with the German road and railway sleep disturbance study
We obtained the original motility and noise data from the German researchers, with motility assessed in 30-s intervals. For comparison, we calculated from the data in the present investigation and those from the reference locations in the aircraft study, with motility measured in 15-s intervals, motility in 30-s intervals. With respect to the German noise data, it was to our opinion not possible to assess indoor traffic noise exposure of subjects with sufficient accuracy. Therefore we did not determine

5 Griefahn B, Möhler U, Schümer R.(Hrsg). Vergleichende Untersuchung über die Lärmwirkung bei Strassen- und Schienenverkehr (Hauptbericht-Textteil, Kurzfassung, Abbildungen und Tabellen,Dokumentationsanhang). München: SGS; 1999.
Möhler U, Liepert M, Schümer R.(Hrsg), Griefahn B. Differences between Railway and Road Traffic Noise. J Sound Vib 2000; 231(3):853-864.

exposure-effect relationships with that noise metric. Instead, we assessed (the increase of) motility as a function of time for four subgroups of the German subjects, classified by gender and type of noise source (road and railway traffic noise). In the German investigation *p40db* of the road and railway locations turned out to be high: on average 58% at the road traffic locations and 61.5% at the railway traffic locations, and at any location *p40db* was over 30%. Therefore, confirmation of the importance of the absence of low background levels on motility could not be fully achieved. What could be shown is that our model (no effect on motility of indoor traffic noise exposure in women, but effects in men, and a small impact on motility of women and men of *p40db* at high values of *p40db* (low background noise levels) and a large impact of at low values of *p40db*) matches the results in a perfect way:

- motility as a function of time after sleep onset in German female subjects both at the road and railway traffic locations are identical to motility as a function of time after sleep onset in female subjects at the reference locations in the aircraft study (*p40db* equal to 57%)
- motility as a function of time after sleep onset in German male subjects both at the road and railway traffic locations is less than motility in the present study for male subjects
- motility as a function of time after sleep onset in German male subjects at railway locations is larger than that of motility in German male subjects at road traffic locations. This is in line with the higher *outdoors* traffic noise exposure in subjects at railway locations.

Self-registered awakening

	night
mot	++
awak	++
heart	+
diary	-/+

The average value during a sleep period of the probability of self-registered awakening in a 15-s interval is an increasing function of *indoor traffic noise exposure*. Gender does affect this function. At the same *indoor traffic noise exposure*, the average probability of self-registered awakening is larger in women than in men. It increases over the exposure range obtained from 1.3 to 2 times per sleep period in women and from 1.1 to 1.5 times per sleep period in men.
We also established a relationship between self-registered awakening and *total indoor noise exposure*. This relationship is weaker than the one with *indoor traffic noise exposure*.
It appears from our results that at a given level of *indoor traffic noise exposure*, motility is larger and self-registered awakening lower in men than in women. Women do not show an effect of traffic noise on motility, but they do on self-registered awakening. This suggests that there are differences between men and women in the factors that play a role in motility and in self-registered awakening.

Heartbeat variables

	night
mot	++
awak	++
heart	+
diary	-/+

We could not establish relationships between noise exposure and heartbeat variables averaged over a sleep period (heart rate in beats per minute, IBI in ms and variability in IBI in ms). Neither did we obtain a relationship between *indoor traffic noise exposure* and changes over a sleep period in heart rate and IBI. Effects do occur on the change over a sleep period in *variability in IBI*. In subjects with a relatively small *variability in IBI* at the start of the sleep period, *variability in IBI* decreases as a function of *indoor traffic noise exposure* and in subjects with a relatively large *variability in IBI* at the start of sleep period the change is nil.

Variables from the diaries

We established relationships of *total indoor noise exposure* with three variables obtained from the diaries: ‘difficulty to fall asleep’, ‘feeling rested after awakening’, and ‘perceived sleep quality after awakening’. We did not find relationships with *indoor traffic noise exposure*.

	night
mot	++
awak	++
heart	+
diary	-/+

2.3.3 *Effects during sleep latency period*

The sleep latency period increases with indoor traffic noise exposure, on average from 17 to 21 minutes over the range of exposures found. Indoor noise exposure caused by non-traffic related noise during the sleep latency period is a confounder: the increase of sleep latency period with indoor traffic noise exposure can be explained by nearly 50% from the non-traffic related noises.

	night
duration	+
heart	-
diary	-

2.3.4 *Effects during the day and evening after a sleep period*

At five times during the day (around 10.00, 12.30, 15.00, 17.30, and 20.00 hours) subjects recorded their sleepiness/tiredness on a card. We could not establish relationships with indoor noise exposures during sleep. The results did show that subjects felt much more tired/sleepy in the evening than in the morning.

	night
daytime sleepiness	-

2.4 Effects over six nights and long-term variables from the questionnaire

2.4.1 *Introduction*

The noise metrics we used to characterize noise exposure during the six sleep periods of subjects are *the equivalent sound level outdoors* over the six sleep periods minus *oid*, denoted by the ‘aggregated indoor traffic noise exposure’, and the *equivalent sound level indoors* over the six sleep periods, denoted by the ‘aggregated total indoor noise exposure’.

	ag,lt
mot	++
awak	-
heart	-/+
diary	n.a.
quest	++

2.4.2 *Motility, self-registered awakening, and heartbeat variables*

The relationships of mean motility and mean motility onset aggregated over the over six sleep periods with the aggregated noise metrics are not different from the results obtained for a sleep period.

On an aggregated level we could not establish relationships between self-registered awakening and noise metrics. Only one relationship was found between heartbeat variables and aggregated noise exposure: variability of IBI decreases with increasing *aggregated total indoor noise exposure*.

	ag,lt
mot	++
awak	-
heart	-/+
diary	n.a
quest	++

2.4.3 *Variables from the questionnaire*

We assessed relationships between *aggregated indoor traffic noise exposure* and

- five effect variables obtained from the questionnaire, which concern nighttime traffic noise exposure (‘degree of annoyance due to noise from the traffic source in the bedroom’, ‘dissatisfaction with noise from the traffic source in the bedroom’, ‘frequency of sleep disturbance due to noise from the traffic source’, ‘degree of sleep

	ag,lt
mot	++
awak	-
heart	-/+
diary	n.a.
quest	++

disturbance due to noise from the traffic source in the bedroom', 'frequency of being awakened by noise from the traffic source in the bedroom')

- one 'general source-related noise annoyance' variable ('annoyance due to noise from the traffic source in the dwelling')
- two general health variables that may not exclusively be related to nighttime traffic noise exposure: 'general sleep quality' and 'self-perceived health'.

We consider it plausible that the five variables from the questionnaire about effects from nighttime traffic noise exposure and about general sleep quality are causally related with *nighttime indoor traffic noise exposure*. The rather weak relationships of self-perceived health and general source-related annoyance with *nighttime indoor traffic noise exposure* may have been affected by *traffic noise exposure during the day and evening*, although it is impossible to draw a decisive conclusion due to lack of information on these *day and evening time exposures*.

3 Associations and correlations between effect variables

3.1 Introduction

For a good view of the effects of traffic noise exposure during sleep on effect variables, it is also important to consider the relations between them. We considered relations for effect variables obtained for a sleep and sleep latency period, and for variables aggregated over six sleep periods and long-term variables obtained from the questionnaire. In the last situation for each subject only one value of an effect variable is obtained. Then, the association between two effect variables can be expressed in the correlation coefficient. In those cases the correlation coefficients have been the basis for expressing the association between variables. Usually, for the effect variables obtained for a sleep period (and a sleep latency period), each subject supplies six values of each effect variable, which requires a different type of analysis (multi-level), and the strength of relations quantified by different measures.
The results are summarized in small tables, similar to the former summary tables. Four types of effect variables are discussed: motility, self-reported awakening, heartbeat variables and variables obtained from the diaries or obtained from the questionnaire. The following symbols have been used in these small tables:

- ++ one or more of a type of effect variables have a strong (statistically significant) relationship with another type of effect variables
- + at least one effect variable of a type has a (statistically significant but relatively weak) relationship with an effect variable of another type.

3.2 Associations of effect variables during a sleep period and a sleep latency period

Sleep period

Night	mot	awak	heart	diary
mot		++	+	+
awak	++			+
heart	+			++
diary	+	+	++	

Motility and *motility onset* are strongly correlated with *self-registered awakening*. At the same average motility, the probability of self-registered awakening is higher in women than in men. To a lesser extent *motility* and *heart rate* are also associated. At the same average motility, the heart rate of women is 9 beats per minute higher than of men. If the motility increases over the range observed, heart rate increases with 5 beats per minute.
We observed associations of *motility* and of *self-registered awakening* with several variables from the diaries, viz. '*noise annoyance in the evening*', '*feeling rested in the morning*', '*sleep quality perceived after awakening in the morning*', '*number of remembered awakenings during sleep period*', '*presence of traffic noises that made falling asleep difficult*', and '*use of hearing protection*'. The association is strongest between the *number of self-registered awakenings* and the *number of remembered awakenings*. If the *number of self-registered awakenings* increases from 0 to 4, the *number of remembered awakenings* increases from 0.9 to 3.1.
We also found associations between *heartbeat variables* and '*feeling rested perceived after awakening*' and '*sleep quality perceived after awakening in the morning*'.

Sleep latency period

The length of the sleep latency period is associated with 'sleepiness in the evening at bedtime', 'the expectation not to be able to fall asleep easily', 'difficulty falling asleep expressed next morning', 'estimated duration (next morning) of sleep latency period', 'use of sleeping pills or sleep inducing drugs (sleep latency period is longer in subjects that use a sleeping pill before going to bed or later in the night)', and 'sleep quality perceived next morning'. The higher heart rate during sleep latency period, the less favorable sleep quality is perceived next morning.

The length of the sleep latency period estimated by the subjects is strongly correlated with the length of sleep latency period derived from the actimetric recordings and the time the marker was pressed at the start of trying to fall asleep. At 18.5 minutes, estimated and calculated values are equal. At longer and shorter sleep latency periods differences do exist between estimated and calculated sleep latency periods.

3.3 Correlations of aggregated effect variables and long-term variables

Agg, lt	mot	awak	heart	quest
mot		++	+	+
awak	++			+
heart	+			++
quest	+	+	++	

There are many correlations between *self-reported awakening* and variables from the questionnaire that are related to *sleep quality*. Apparently, the fact that subjects wake up during the sleep period has an important effect on their rating of their general sleep quality and their sleep disturbance by the traffic noise source. On the other hand, *self-reported awakening* does not seem to have impact on *self-perceived health*, *self-perceived vitality*, and *(degree of) depression*. These variables are correlated with *motility* and *motility onset*. *Motility* and *motility onset* are also correlated with clinically defined *sleepiness in present and/or past*, and *motility* also with *noise sensitivity*, and *number of sleep complaints*.

Heart rate and *IBI* have a strong association with *self-perceived health*, *self-perceived vitality*, *sleep complaints*, *complaints about sleepiness in present and/or past*, and with *level of education*. The associations of *self-perceived health* and the *heartbeat variables* are much stronger than the association of *self-perceived health* with *motility*. E.g., if *IBI* changes over the full range of observed values, *self-perceived health* increases by nearly 7 points (on a 21-points scale), and if *motility* changes over the full range of observed values *self-perceived health* increases by only 2 points on the same scale.

4 Comparison of effects of nighttime road and railway traffic noise

At the same level of *indoor traffic noise exposure* the mean motility and the mean motility onset over a sleep period or aggregated over six sleep periods are considerably less at railway traffic locations than at road traffic locations. This can be explained by the low background levels at the railway locations. The same factor may explain that at railway locations acute effects on motility and motility onset of railway noise events of average duration are somewhat less than from road traffic noise events of the same duration. For the 2.5% observed railway noise events of long duration (on average one train passage per two nights in the four hours in the middle of the night considered), railway traffic noise-induced motility and motility onset are larger than noise-induced motility and motility onset for road traffic noise events.

None of the other effect variables did show a dependency on the noise source. Therefore we conclude that it is quite unlikely that railway traffic noise at the same level of *indoor traffic noise exposure* as road traffic noise has a larger effect on the variables considered than road traffic noise; we expect on the contrary that the effects at the same level of *indoor traffic noise exposure* are less. However, a definite conclusion about the large impact of low background noise levels on motility awaits confirmation from other studies.

5 Conclusion

The analyses showed that nighttime traffic noise has adverse effects on sleep. The results show a consistent pattern. Motility, motility onset, self-reported awakening, and heart rate increase and reported sleep quality decreases with increasing road and railway indoor noise exposure during sleep.
On the basis of more than 48000 effect evaluation intervals of subjects, an acute increase in motility and motility onset during noise events was demonstrated. On average the probability of motility increases with 10 and 50% of the overall probability of motility due to the loudest noise events found at, respectively, 0.5 and 4.5 hours after sleep onset. This finding is remarkable, as subjects are chronically exposed to many noise events each night.
The observed acute effects of road and railway noise events on heart rate are limited. We could not establish relationships between traffic noise events and heart rate, but only between all noises in the bedroom (including traffic noise events) and heart rate. Moreover, there is hardly an acute reaction observed in men. In women heart rate increases on average by 2.5 beats during one minute due to the loudest traffic noises of average duration.
An acute effect on self-registered awakenings could not be demonstrated.

On the basis of 1572 subject nights (and 172 subject nights with heartbeat data) effects of traffic noise exposure during the sleep period on average motility during sleep, on changes in heart rate over a sleep period, and on (average) self-registered awakening during a sleep period have been established. The results show that the average motility of women during sleep is not influenced by traffic noise events, but also that women are (nearly) equally sensitive as men to noises in the bedroom not related to traffic noise. Self-registered awakening increases with traffic noise exposure, whereby women react more often than men at the same indoor traffic noise exposure during sleep period.
The present field study suggests that high background noise at the road traffic locations, especially motorways, strongly affects the average motility and motility onset. A secondary analysis of two large data sets was not able to fully confirm this finding, presumably due to a lack of locations with high background noise in those studies.

The data aggregated over six nights show the same results on motility as found on the basis of the single nights, no effect on self-registered awakening and decreased variability in heart rate.

The comparisons of the results for road traffic noise with those for railway traffic noise show that it is very unlikely that railway traffic negatively affects sleep to a larger extent than road traffic with the same indoor noise exposure, and that possibly the effects of railway traffic at the same indoor noise exposure are less.

Since the study did not include children, persons with nightshifts, and seriously ill people as subjects, the results do not relate to these people. We assume that the results are representative for the general population, since exclusion criteria for the subjects have been hardly used, there was no indication of bias by selective response of the participating subjects, and data have been collected irrespective of traffic noise exposure. We cannot exclude that nighttime noise may have a different effect than found in this study on populations with living conditions that strongly differ from those in the Netherlands.

The way ahead

It is most desirable, from a scientific as well as from a policy point of view, that a study of sufficient size is undertaken to confirm the present finding that high background noise, especially near motorways, has a large impact on motility during sleep. In that study, not only A-weighted sound levels should be measured, but also the low frequency components in the background noise should be taken into account.

Field studies of sufficient size should be undertaken to further explore the effects of nighttime environmental noise on cardiovascular factors.

The present study showed a weak association between perceived health and nighttime traffic noise exposure, which is presumably affected by daytime environmental noise exposure. A study especially designed to assess relationships of health effects and perceived health effects with nighttime noise exposure, might be undertaken.