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Sleep disturbances from road traffic and ventilation noise—laboratory and field experiments

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Abstract

The aims of this study were to assess the effects on sleep of different types of noise exposures (road traffic, ventilation and combination of noise from road traffic and ventilation) and compare effects on sleep both in laboratory and in field settings. Eighteen subjects slept 1 week in the laboratory and 1 week in their home and their sleep was evaluated with wrist actigraphs and questionnaires on sleep and mood. In the laboratory, judged sleep quality was decreased by 22% during nights with exposure to road traffic noise in the laboratory compared to the quiet reference night. The combined noise from ventilation and road traffic caused more awakenings; worse sleep quality (−25%) and more movements reported by questionnaire. None of these significant results were detected by actigraphy. Noise from ventilation caused a decrease in judged sleep quality by 12%, while sleep assessed by actigraph indicated better sleep as compared with the quiet reference night. When comparing sleep with traffic noise exposure in the laboratory and in the home the results show no differences on sleep effects.

1. Introduction

Field studies and laboratory experiments on noise-induced sleep disturbance show conflicting results and the accuracy of the results from laboratory experiments on sleep has sometimes been called into question, e.g., Ref. [1]. It is known from a comparison of results from field studies versus studies with short-term and extended exposure in laboratory experiments, that large habituation effects exist for awakenings [1,2], while other effects such as heart rate reactions and minor EEG (electroencephalography) reactions, show no habituation to noise.

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Most research on noise-induced sleep disturbances has been conducted on transportation noise and very few studies have dealt with the effects of ventilation noise on sleep. The experience from Swedish local environmental health authorities is that noise from outdoor ventilation systems mounted in the courtyards, often exceeds the recommended values. Of 20 investigated courtyards in Stockholm (16 chosen because of complaints and four yards chosen randomly), 85% exceeded the evening level recommended for external industrial noise and 100% exceeded the levels recommended during night (40 dB $L_{A\,eq,22-06\,\mathrm{h}}$) [3]. Sleep disturbance due to low-frequency noise has only been studied in one laboratory experiment [4]. The study was limited to the effects on EEG, EOG (electroocculography) and other physiological effects, where no effects due to low-frequency noise were found. However, no records were obtained of the time of falling asleep or how the subjects felt in the morning, variables that seem to be more relevant for effects of low-frequency noise exposure. Furthermore, the noises used do not correspond to a real exposure situation. There is thus a great need to study effects of low-frequency noise on sleep.

As stated in the Swedish Action Plan Against Noise [5], it will take time to thoroughly come to grips with traffic noise. It is vital to attenuate (or reshape the spectrum of) noise from ventilation systems, which often destroys an otherwise quiet environment in courtyards or at the rear of the building that is shielded from traffic noise. Many people have a desire to sleep with open windows, but ventilation systems and fans mounted on the roof or in the courtyard prevent them from doing so.

Studies on time taken in falling asleep, effects of noise during sleep, premature awakening, judged sleep quality and after-effects of noise-disturbed sleep, such as sleepiness and changes in mood after exposure to night-time noise, should be performed. When studying the effects of night-time noise on various measures of sleep disturbance, it is important that the individual exposure is at least known, and preferably kept under control [6–8]. For the evaluation of possible reasons for the discrepancies found, studies both in field and in well controlled laboratory settings are necessary.

The present study is part of a larger research programme "Soundscape Support to Health"[9]. The main goals of this programme with reference to sleep quality and noise-induced sleep disturbances are: (1) to provide knowledge on the efficiency of different noise abatement procedures in reducing adverse effects of noise on sleep, used as input for the overall evaluation, promotion and implementation of optimal noise abatement activities directed towards a sustainable acoustic environment in residential areas; (2) to provide knowledge on the impact on sleep quality of noise from ventilation, often prevalent in courtyards of residential buildings in city centres, and thereby to provide information on the importance on sleep quality of soundscapes with access to quiet indoor areas at night; (3) to improve methodologies for assessment of effects on sleep and to provide tools for assessment of direct adverse effects of noise on sleep, to be applied especially for strategic environmental health impact assessments in connection with existing and new residential areas.

Two series of laboratory and field experiments on noise-induced sleep disturbances are performed within this programme. In the first series of experiments, people who live in rather quiet residential areas are chosen. They are exposed to recorded noise from traffic, ventilation and a combination of these exposures, in the laboratory and to the same traffic noise exposure in their own homes. In a second series that will be presented in another paper, subjects who live along a busy street with their bedroom windows facing the street are exposed to their "home noise" in the laboratory.

2. Aim of the study

One aim of the first series of experiments is to assess effects on sleep of different types of noise exposure:

(1) Noise from road traffic.
(2) Noise from ventilation.
(3) A combination of noise from road traffic and ventilation.

Other aims concerning methodological issues:

(4) What are the most sensitive indicators for effects of noise on sleep; sleep variables such as difficulties to fall asleep, awakenings, sleep quality, tiredness and mood in the morning assessed by questionnaire or sleep assessed by actigraphy?
(5) Are there differences in results for sleep studies performed in laboratory and in field settings?

3. Test subjects and methods

3.1. Test procedure

The test subjects slept six consecutive nights in the sleep laboratory and six consecutive nights in their homes. The subjects were informed that whey should be exposed to recorded sounds typical for a dwelling in a city along a street with traffic noise and other typical city sounds. No information was given about the aim and the exposure design of the study. They were asked to go to bed at 22:50, to turn off the light at 23:00 and they were woken up by an alarm clock at 07:00 in the morning. The subjects were supplied with alarm clocks that were synchronized against the time settings of the actigraphs. During the night, body movements were registered by an actigraph. In the evening, the subjects answered a questionnaire on feelings of tiredness and stress during the day and evening. They were asked to press a button on the actigraph, both when they turned off the light to go to sleep and in the morning, to mark the time they woke up. They then answered a questionnaire concerning the previous night's sleep. A mood questionnaire was also answered each evening and morning (Table 1).

The first two nights (quiet and condition A, respectively) in the laboratory were for habituation to the laboratory conditions and to the actigraph. The third night was a quiet reference night and during the remaining three nights, subjects were exposed to recorded noise from road traffic (A), ventilation noise (B) or a combination of noise from ventilation and road traffic (C).

Half of the subjects slept the first week of the experiments in the laboratory and the second week in their home. The other half of the subjects slept in the opposite order. When the subjects slept in their own homes, the first three nights of the design were equal to the laboratory. During

Table 1
The design used in the laboratory

Session	Night 1	Night 2	Night 3	Night 4	Night 5	Night 6
	Habituation	Habituation	Ref quiet	Exposure	Exposure	Exposure
1	Quiet	A	Quiet	A	B	C
2	Quiet	A	Quiet	B	C	A
3	Quiet	A	Quiet	C	A	B
4	Quiet	A	Quiet	A	C	B
5	Quiet	A	Quiet	B	A	C
6	Quiet	A	Quiet	C	B	A
7	Quiet	A	Quiet	A	C	B
8	Quiet	A	Quiet	B	A	C
9	Quiet	A	Quiet	C	B	A

the last three nights, subjects were exposed to recorded noise from road traffic (condition A) only. In this study, two subjects at a time participated.

3.2. Test subjects

Thirteen female and five male healthy students took part in the study, aged 18–30 (average age 22.8, SD 2.85, median 22.0). All 18 passed the audiometric test and none of them used any type of medication. Noise sensitivity was assessed by 20 of the 21 statements of Weinstein's scale [10], which results in 20 points as the lowest noise sensitivity and 120 points as the highest noise sensitivity. Their noise sensitivity varied between 47 and 91, with a mean value of 69.7 (SD 13.35) and a median of 67. A four-pointed scale also evaluated noise sensitivity: (1) not at all sensitive to noise, (2) not very sensitive, (3) rather sensitive and (4) very sensitive to noise. Among the subjects, seven were rather sensitive to noise, nine were not very sensitive and two were not at all sensitive to noise. The subjects lived in dwellings situated in Gothenburg municipality, with rather quiet surroundings and without trams, trains or busy roads in the neighbourhood.

3.3. Sleep laboratory

The study was performed in a sleep laboratory consisting of a simulated dwelling with three bedrooms, a sitting room and a kitchenette. The temperature in the bedrooms was adjusted according to the subject's requests. The subjects had their own keys to the flat and could come and go as they pleased during the day. They usually came to the laboratory early in the evening, and had time to relax before going to bed. During the test period, sleep during daytime hours or consumption of alcohol was not permitted.

3.4. Noise exposure

The noise exposure started at 22:30 and continued until 07:30 in the morning. The registration period for sleep and noise (time from lights out to time of getting up in the morning) lasted from

23:00 until 07:00 in the morning. The exposure consisted of three types of noise; noise from road traffic (A), ventilation (B) and a combination of these (C).

Condition A consisted of noise from road traffic, recorded outdoors beside a motorway and mixed to consist of a total of 64 passing vehicles with a maximum level of car passages of 55 ± 3 dB $L_{A(f)max}$. The background level of the continuous traffic noise was 32 dB $L_{A\ eq,23-07\ h}$ and the total level was 39 dB $L_{A\ eq,23-07\ h}$. During the night, the number of vehicles was reduced to give a noise level reduction of 6 dB between 01 and 05 o'clock to simulate natural noise conditions. During the first and the last 3 h there were 12 vehicle passages per hour; and between 01–02 and 04–05 h, there were six passages per hour; between 02 and 04 there were two passages per hour. The frequency spectrum of the road traffic noise was adjusted during playback to simulate an open window situation, with the window open 10 cm.

Noise condition B consisted of noise from outdoor ventilation systems mounted in a courtyard in Gothenburg city. The noise was recorded indoors in an office room facing the courtyard with the window open 10 cm. The noise level was set to 40 dB $L_{A\ eq,23-07\ h}$.

Noise condition (C) was a combination of noise from traffic (A) and noise from ventilation (B). The $L_{A\ eq,23-07\ h}$ level was 43 dB and the $L_{A\ max}$ level was 55 ± 3 dB. The noise level during the quiet reference night was 25 dB $L_{A\ eq,23-07\ h}$. Fig. 1 shows the frequency spectra for the different noise exposures.

For the night-time noise exposure, a Fostex VR-800 hard disk recorder was used. A hidden loudspeaker, a Genelec-1081 studio monitor, was built into the wall above the false window in the bedrooms of the sleep laboratory. The exposure level was calibrated using a B&K sound level meter, type 2260 with the microphone positioned on the pillow.

The same type of equipment for generating noise exposure was used in the laboratory and in the subjects' own homes. When the subjects slept in their own homes, the noise exposure was calibrated at their pillow position to obtain the same sound levels as in the sleep laboratory. The playback equipment was placed in an adjacent room during the whole experiment to avoid disturbing the subject.

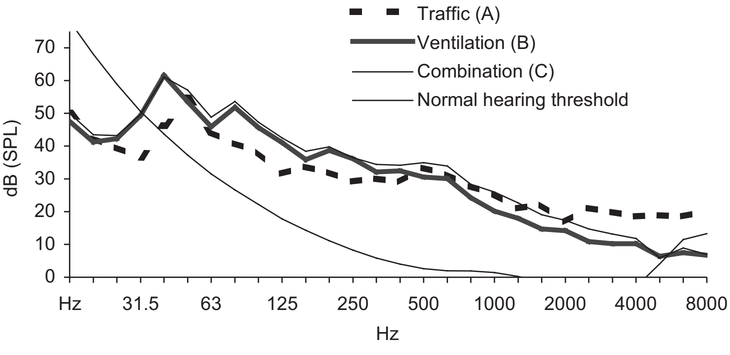

Fig. 1. Frequency spectra for the different types of exposure noise used in the experiment.

4. Evaluation of effects

4.1. Wrist actigraph

Body movements were registered by using a wrist-actigraph type Mini-motion-logger actigraph tri-mode from Ambulatory Monitoring Inc. The same two actigraphs were used throughout the experiment. The movement sensor is a piezo-electric beam with capability of detection in all three axes. A button on the actigraph makes it possible to log pre-arranged events. Action-W, version 2.3.20 [11] and ACT 2000 [12] were used to manage and evaluate data from the actigraphs. Data was downloaded to a computer for analysis of the following variables: duration, activity mean, wake minutes, sleep minutes, % sleep, sleep efficiency, sleep latency, wake after sleep onset, wake episodes, mean wake episode, long wake episodes, sleep episodes, mean sleep episode and long sleep episodes. Results for most of the variables are presented in this paper.

The variables are defined as follows:

Duration: time in bed from the moment the button was pressed on the actigraph and the light turned out in the evening, until it was pressed after waking up in the morning. *Activity mean:* mean activity score from counts registered by the actigraph per 30 s, which was the chosen time period. *Wake minutes:* total minutes scored as wake. *Sleep minutes:* includes total minutes scored as sleep. *Percent Sleep:* percent minutes scored as sleep. *Sleep latency:* calculated as minutes to start of first 20-min block with more than 19 min of sleep according to the Cole–Kripke sleep-scoring algorithm [13]. *Wake after sleep onset:* is wake minutes duration time with sleep latency excluded. *Wake episodes:* the number of blocks of contiguous wake epochs. *Mean wake episode*: mean duration in minutes of the wake episodes. *Sleep episodes:* the number of blocks of contiguous sleep epochs. *Mean sleep episode:* mean duration in minutes of sleep episodes.

4.2. Questionnaire on judged sleep quality

Sleep quality was evaluated by slightly elaborated, previously used questionnaires (e.g., [14]). Every evening, within 15 min before going to bed, the subjects completed a questionnaire with questions on feelings of stress and feelings of tiredness during the day and evening. The questions were evaluated with both a linear 100 mm scale and a ten-degree numerical scale with figures from zero to ten. The endpoint markings were "very stressful/not at all stressful" and "tired/alert", respectively.

Every morning, within 15 min after awakening, a questionnaire on judged sleep quality was completed. The questionnaire included questions on time in falling asleep and reasons if there were difficulties in falling asleep, sleep quality, movements during the night, number of and reasons for awakenings, and feelings of tiredness in the morning. To assess sleep quality, movements and tiredness were evaluated with two types of scales as described in the evening questionnaire, with the endpoint markings "very bad/very good", "moved hardly at all/tossed around all night" and "tired/alert" in the morning. There was also space in the questionnaire to make personal comments about the night's sleep.

4.2.1. Mood questionnaire

Mood was evaluated each evening and morning using a mood adjective checklist [15], comprising 71 adjectives measuring "hedonics", "extroversion", "social orientation", "activity", "relaxation" and "security". A four-degree scale from "completely agree" to "completely disagree" was used.

4.3. Statistical analyses

Wilcoxon's test and Chi-square or Fisher's test were used to evaluate differences on effects between nights. Mann–Whitney's test was used to evaluate differences between individuals with different noise sensitivity. Spearman's rank correlation test was used to test correlations between variables. Two of the subjects had large problems in falling asleep (sleep latency around 3 h) during one and two nights, respectively, with the traffic noise exposure in the home. The values for these nights were considered outliers, and were excluded from the analyses. In the home, the subjects were exposed to traffic noise during three consecutive nights. As no significant differences between the nights were found an average of the three nights was used in the analyses. As the results from correlation analysis on the scales 0–100 and 0–10 for judged sleep variables were high, only the results on the 0–100 scales are presented. All tests were one-sided and p-values below 0.05 were considered statistically significant.

5. Results

5.1. Effects of different types of noise exposure in the laboratory

5.1.1. Sleep assessed by actigraphy

Table 2 shows the results on sleep assessed by actigraphy as mean values (m) and standard deviation (SD) for different noise exposures in the laboratory sessions. As seen in the table, there

Table 2
Sleep assessed by actigraphy for quiet nights and nights with different noise exposure in the laboratory

	Quiet		Traffic		Ventilation		Combined	
	M	SD	M	SD	M	SD	M	SD
Duration, minutes	481	(2.7)	481	(2.1)	481	(3.0)	481	(2.5)
Activity mean, score	6.4	(3.5)	6.5	(3.9)	5.7	(3.2)	6.3	(2.9)
Sleep latency, minutes	13.6	(12.6)	10.7	(9.8)	10.4	(9.6)	11.3	(12.4)
Wake minutes after sleep onset	19.1	(29.9)	20.4	(31.5)	15.5	(26.6)	19.1	(21.7)
Wake episodes, number	7.9	(6.1)	7.2	(5.3)	7.0	(5.7)*	7.1	(4.3)
Mean wake episodes, minutes	3.8	(2.2)	3.7	(2.3)	4.0	(2.2)	3.6	(1.9)
Sleep minutes	449	(31.4)	450	(36.5)	455	(27.3)	451	(26.3)
Sleep episodes, numbers	7.3	(6.2)	6.8	(5.3)	6.6	(5.6)*	6.7	4.2
Mean sleep episodes, minutes	116	(80.9)	124	(110.5)	182	(173.7)*	106	(74.0)

* Significant difference between the quiet night and the ventilation exposure night.

were large variations in sleep measured with actigraphs between different individuals and irrespectively of exposure condition. For example, in the quiet condition was the highest score for activity mean was 13.6 and the minimum score was 2.7. The score for number of sleep episodes varied from 2 to 22.

No significant differences were found for any variables between the quiet reference night and traffic exposure or the quiet night and the combined exposure.

Significant differences were found between the quiet night and the night with ventilation noise for some sleep variables. These differences indicate better sleep during the night with ventilation noise. Fewer numbers of wake episodes ($p = 0.03$) was found during the night with ventilation noise. Mean sleep episodes were 67 min longer ($p = 0.02$) and the number of sleep episodes was fewer ($p = 0.03$) during the night with ventilation noise than during the quiet night.

5.2. *Sleep quality assessed by questionnaire*

Results on judged sleep quality for the quiet night and exposure to traffic, ventilation and the combination of traffic and ventilation noise in the laboratory are shown in Table 3. Significant differences were found between the quiet night and the different types of noise exposure for some sleep variables.

The number of awakenings was higher during the night with combined noise exposure ($p = 0.042$) while the increase in awakenings during the night with traffic noise did not reach significance. Sleep quality decreased significantly during all exposure nights in comparison with the quiet night (traffic $p = 0.016$; ventilation $p = 0.049$; combined $p = 0.008$). Sleep quality was significantly better during nights with ventilation noise compared with traffic noise ($p = 0.047$). The mean value of subjective movements was higher ($p = 0.012$) during the night with combined exposure.

Table 3
Results from judged sleep variables for the quiet night and nights with different noise exposure in the laboratory sessions

	Quiet		Traffic		Ventilation		Combined	
	M	SD	M	SD	M	SD	M	SD
Minutes to fall asleep	19.9	(12.8)	19.1	(14.5)	17.3	(12.5)	18.4	(14.7)
Difficulties to fall asleep, %	22.2		17.7		22.2		22.2	
Awakenings, number	0.89	(0.9)	1.44	(1.29)	0.89	(1.08)	1.44	(1.10)*
Sleep quality (0–100)[a]	74.6	(17.0)	58.4	(23.0)*	65.4	(22.1)*	55.8	(26.2)**
Movements (0–100)[a]	33.6	(18.7)	39.2	(22.2)	36.8	(20.1)	47.4	(22.1)**
Tired–alert morning after (0–100)[a]	37.1	(16.4)	42.9	(22.5)	32.7	(18.5)	32.7	(17.4)
Tired–alert day after (0–100)[a]	55.3	(23.8)	50.5	(23.7)	60.8	(24.2)	50.9	(21.3)

*Significant difference between the quiet night and different exposure nights.
**$p = 0.01$.
[a] Higher average means better sleep quality, more movements and more alert in the morning.

6. Effects of traffic noise exposure in the laboratory and in the home

6.1. Sleep assessed by actigraphy

There were large variations in sleep measured with actigraphy between different individuals also in the home situation. For example, the highest score for activity mean was 11.3 and the lowest was 2.1. The number of sleep episodes varied from 1 to 21 during the quiet night at home.

No significant differences were found between the quiet night in the home and the quiet night in the laboratory in any of the sleep variables assessed by actigraphy, while significant differences were found for some variables between traffic noise exposure in the home compared to the same exposure in the laboratory (see Table 4).

When comparing nights with traffic noise exposure in the home and in the laboratory, duration of sleep was found to be slightly shorter (on average 2 min), $p = 0.008$ and sleep latency was about 6 min longer ($p = 0.02$) in the home than in the laboratory. Mean wake episodes in minutes was about 1 min longer ($p = 0.027$) and sleep minutes was 11 min shorter ($p = 0.03$) in the home.

Significant differences in the home between the quiet night and the night with traffic noise were found for two of the actigraph variables. During traffic noise exposure in the home, activity mean was higher (7.1 versus 6.1, $p = 0.016$) and sleep minutes was 9 min shorter ($p = 0.029$) compared to the quiet night.

6.2. Sleep quality assessed by questionnaire

Results from the quiet nights and the nights with traffic noise exposure in the laboratory and at home are shown in Table 5. When comparing the quiet nights in home and in the laboratory, only

Table 4
Sleep assessed by actigraphy for quiet nights and nights with traffic noise exposure in the home and in the laboratory

	Quiet				Traffic			
	Home		Laboratory		Home		Laboratory	
	M	SD	M	SD	M	SD	M	SD
Duration, minutes	479	(4.0)	481	(2.7)	478	(3.2)	480	(2.1)**
Activity mean, score	6.1	(3.2)	6.4	(3.5)	7.1	(3.9)[a]	6.5	(3.9)
Sleep latency, minutes	12.1	(13.8)	13.6	(12.6)	16.3	(11.3)	10.7	(9.8)*
Wake minutes after sleep onset	19.1	(26.8)	19.1	(29.9)	24.0	(27.9)	20.4	(31.5)
Wake episodes, number	7.5	(6.3)	7.9	(6.1)	9.1	(7.8)	7.2	(5.3)
Mean wake episodes, minutes	4.8	(3.7)	3.8	(2.2)	4.8	(2.5)	3.7	(2.3)*
Sleep minutes	448	(30.7)	449	(31.4)	439	(33.5)[a]	450	(36.5)*
Sleep episodes, numbers	6.9	(6.2)	7.3	(6.2)	8.6	(7.6)	6.8	(5.3)
Mean sleep episodes, minutes	171	(173.6)	116	(80.9)	145	(113.9)	124	(110.5)

*Significant differences for traffic at home versus traffic in laboratory.
**$p = 0.01$.
[a] Significant differences for traffic at home versus quiet at home.

Table 5
Results from judged sleep for quiet nights and nights with traffic noise exposure in the home and in the laboratory

	Quiet				Traffic			
	Home		Laboratory		Home		Laboratory	
	M	SD	M	SD	M	SD	M	SD
Minutes to fall asleep	16.7	(11.9)	19.9	(12.8)	22.9	(18.5)**	19.1	(14.5)
Difficulties to fall asleep, %	0		22.2		30.0		17.6	
Awakenings, number	1.17	(0.86)	0.89	(0.90)	1.61	(1.01)	1.44	(1.29)
Sleep quality (0–100)	77.6	(19.8)	74.6	(17.0)	61.7	(17.5)**	58.4	(23.0)
Movements (0–100)	31.6	(23.5)	33.6	(18.7)	41.7	(16.4)*	39.3	(22.2)
Tired–alert morning after (0–100)	54.0	(23.7)	37.1	(16.4)[a]	43.5	(18.5)*	42.9	(22.5)
Tired–alert day after (0–100)	58.3	(26.9)	55.3	(23.8)	52.5	(20.5)	50.5	(23.7)

* Significant differences for traffic at home versus quiet at home.
** $p = 0.01$.
[a] Significant differences for quiet at home versus quiet at laboratory.

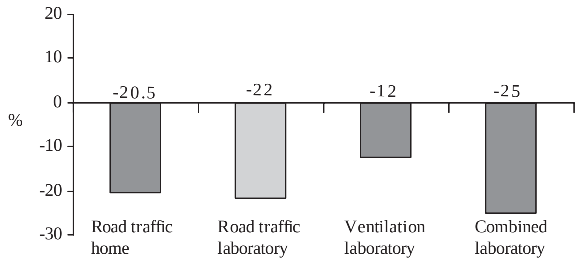

Fig. 2. Differences in percentage for sleep quality in the laboratory and at home for traffic noise, and in the laboratory for ventilation noise and combined noise compared to a quiet reference night.

a significant difference between tired–alert in the morning was found, the subjects being more ($p = 0.008$) tired in the morning in the laboratory than at home. No significant differences were found between the nights with traffic noise exposure in the home and in the laboratory. Between the quiet night in the home and traffic noise exposure in the home, several significant differences were found.

The table shows that during traffic noise exposure, in the home, it took longer to fall asleep ($p = 0.012$), sleep quality decreased ($p = 0.002$) by 7.6%, the subjects moved more ($p = 0.02$) and were more tired in the morning ($p = 0.02$), compared with the quiet night.

Fig. 2 shows differences in percentage for sleep quality in the laboratory and at home for traffic noise, and in the laboratory for ventilation noise and combined noise.

Sleep quality decreased by 22% in the laboratory and 20.5% at home after exposure to traffic noise in comparison to a quiet reference night. Ventilation noise caused a decrease in sleep quality by 12%. The combined noise exposure has about the same effect on sleep quality (–25%) as traffic noise alone.

6.3. Effects on mood

There were no significant differences on the mood variables in the *evening* between different nights, neither in the laboratory nor in the home. Significant differences were found between the quiet night and the nights with different types of exposure for some mood variables in the *morning*. Table 6 shows the results from the morning mood variables in the laboratory sessions.

The morning after traffic noise exposure the test group felt less relaxed ($p = 0.03$) compared to the quiet night. After the ventilation noise exposure, they felt less active ($p = 0.037$), and after the combined noise, they felt less extrovert and less socially oriented ($p = 0.028$ and 0.026, respectively).

Table 7 shows the results on mood in the morning after quiet nights and nights with traffic noise exposure at home and in the laboratory sessions.

The subjects felt somewhat less active ($-8.2\%, p = 0.048$) in the laboratory after the quiet night compared to the quiet night in the home. However, no significant differences on morning mood were found between traffic noise exposure in the laboratory and the home.

Table 6
Results on mood variables in the morning (mean and SD) after the quiet night and after nights with different noise exposure in the laboratory sessions

	Quiet		Traffic		Ventilation		Combined	
	M	SD	M	SD	M	SD	M	SD
Active	2.32	(0.48)	2.40	(0.49)	2.16	(0.47)*	2.25	(0.44)
Extrovert	2.51	(0.49)	2.42	(0.36)	2.35	(0.32)	2.30	(0.34)*
Relaxed	3.04	(0.34)	2.89	(0.46)*	3.00	(0.39)	2.93	(0.42)
Hedonic	2.94	(0.41)	2.86	(0.38)	2.85	(0.46)	2.82	(0.48)
Social	3.01	(0.37)	2.97	(0.36)	2.90	(0.39)	2.86	(0.47)*
Secure	3.11	(0.35)	3.05	(0.30)	3.10	(0.31)	3.06	(0.32)

*Significant difference between the quiet night and the different exposure nights.

Table 7
Results on morning mood variables after quiet nights and nights with traffic noise exposure in the home and in the laboratory

	Quiet				Traffic			
	Home		Laboratory		Home		Laboratory	
	M	SD	M	SD	M	SD	M	SD
Active	2.57	(0.49)	2.32	(0.48)[a]	2.36	(0.44)*	2.40	(0.49)
Extrovert	2.58	(0.44)	2.51	(0.49)	2.46	(0.39)	2.42	(0.36)
Relaxed	2.96	(0.48)	3.04	(0.34)	2.96	(0.35)	2.89	(0.46)
Hedonic	2.98	(0.45)	2.94	(0.41)	2.94	(0.42)*	2.86	(0.38)
Social	3.09	(0.31)	3.01	(0.37)	2.98	(0.41)*	2.97	(0.36)
Secure	3.16	(0.35)	3.11	(0.35)	3.07	(0.28)*	3.05	(0.30)

*Significant differences for traffic at home versus quiet at home

[a]Significant differences for quiet at home versus quiet in lab.

In the morning in the home, the test group felt significantly less active ($p = 0.025$), hedonic ($p = 0.024$), secure ($p = 0.048$) and socially oriented ($p = 0.044$) after traffic noise exposure compared to the quiet reference night. The decrease in mood was small, and varied from 1.3% for hedonic up to 9.7% for active.

6.4. Sleep quality in relation to individual factors

No significant differences were found between the rather sensitive and the less sensitive subjects for any judged sleep variables or sleep assessed by actigraphy.

Significant differences were found between the two genders on all variables assessed with actigraphy ($p < 0.0001$). Men had longer sleep latency, higher activity mean and fewer sleep minutes during the night than women. These differences were not found regarding sleep assessed with questionnaire.

7. Comparison between judged sleep and sleep assessed by actigraphy

Sleep variables measured with actigraphs were highly correlated with one another in most cases ($r_s > 0.80$, $p < 0.0001$). With questionnaires, significant correlations were found between movements and the other judged sleep variables (e.g., movements and awakenings $r_s = 0.40$, $p < 0.0001$). Sleep quality was correlated to time to fall asleep ($r_s = -0.25$, $p = 0.003$) awakenings ($r_s = -0.40$, $p < 0.0001$), movements ($r_s = -0.72$, $p < 0.0001$) and tired in the morning ($r_s = 0.18$, $p = 0.04$) (all data not shown). Beyond that, no significant correlations were found between the judged sleep variables.

Correlations between sleep variables registered by actigraph and by questionnaire show several significant results for the variables awakenings and tired–alert in the morning. Only a few other variables showed significant correlations (Table 8).

Table 8
Correlations (r_s) between sleep registered by actigraph and by questionnaire ($n = 140$ nights)

Variables assessed with questionnaire	Variables measured with actigraph					
	Activity mean	Sleep latency	Wake minutes after sleep onset	Wake episodes, number	Long wake episodes, number	Sleep (minutes)
Minutes to fall asleep	0.10	0.24**	0.13	0.08	0.12	−0.15
Sleep quality 1–100	−0.16	−0.009	−0.17*	−0.14	−0.15	0.09
Tired–alert 1–100	0.35***	0.14	0.28**	0.26**	0.30**	−0.35***
Movements 1–100	0.19*	−0.03	0.21*	0.17*	0.15	−0.10
Awakenings number	0.20*	−0.08	0.24**	0.21*	0.23**	−0.22**
Sleep (minutes)	−0.11	−0.27**	−0.13	−0.07	−0.11	0.17*

*$p = 0.05$.
**$p = 0.01$.
***$p = 0.001$.

The table shows a positive correlation ($r_s = 0.24$) between judged minutes to fall asleep and sleep latency. Sleep quality assessed by questionnaire was correlated to wake minutes ($r_s = -0.17$). Tiredness in the morning was unexpectedly correlated with activity mean ($r_s = 0.35$), wake minutes ($r_s = 0.28$), wake episodes ($r_s = 0.26$), long wake episodes ($r_s = 0.30$) and sleep minutes ($r_s = -0.35$).

Judged movements were correlated to activity mean ($r_s = 0.19$), wake minutes ($r_s = 0.21$) and wake episodes ($r_s = 0.17$). Judged awakenings were correlated to all actigraph variables except sleep latency; activity mean ($r_s = 0.20$), wake minutes ($r_s = 0.24$), wake episodes ($r_s = 0.21$), long wake minutes ($r_s = 0.23$), and sleep minutes ($r_s = -0.22$). Judged sleep minutes was correlated with sleep latency ($r_s = 0.27$) and sleep minutes measured with actigraphy ($r_s = 0.17$).

8. Discussion

8.1. Method

We have chosen wrist-actigraphy because this method is widely used in studies of effects of noise on sleep, e.g., Reyner [16] and Friedman et al. [17]. In a review, Sadeh et al. concluded that actigraphy provides useful measures of sleep-wake schedule and sleep quality and despite its limitations, may be a useful, cost-effective method for assessing specific sleep disorders [18]. In a pilot study, we tested our available ten actigraphs. In a different series of tests, the same person wore two actigraphs one on top of the other on the same wrist. We found large discrepancies between several of the actigraphs. There are individual differences in body motility between individuals and therefore each subject is compared with him/herself [19] and in order to minimize differences in the results due to using different actigraphs, only two actigraphs with similar sensitivity were used throughout the whole study and all subjects used the same actigraph both at home and in the laboratory. The wrist-actigraph measures movements by recording a count each time the signal crosses a defined threshold voltage (zero-crossing technique). This result in "activity counts" where the value is the number of signal zero-crossings that occur in the chosen time period, one movement results in two counts. No amplitude or intensity of the movement is measured by this technique. All calculations of the different variables are made from these counts, which result in relatively high correlations between the different actigraph variables. PSG-registration with continuous and simultaneous recording of physiological variables during sleep is considered to be the most exact method of sleep measurement. High costs and technical difficulties are however associated with PSG-registration. Actigraphy has mostly been used in sleep studies of effects of noise on sleep during the last years and one reason is the convenience for the subjects. The actigraphy method has been criticized, e.g., by Someren who argues that the zero-crossing method does not give a correct measure of the movements because the bandpass filters chosen in commercially available actigraphs are not optimal [20]. In our study, each subject is compared with him/herself, which decreases this problem. Pollak points out that actigraphy overestimates sleep and is not an accurate sleep-wake indicator [21]. Some researchers consider that actigraphy is a more objective method than questionnaires that judge the sleep afterwards, e.g., Reyner [16] and Friedman [17]. On the other hand, some researchers consider that under certain circumstances, subjective sleep is a better indicator of the effects of noise on sleep than objective sleep parameters determined by sleep polygraphy [22]. We did not find any differences between genders for sleep measured by questionnaire but unexpected differences between genders were found for sleep measured with actigraphs, with a higher rate of activity mean for men. This could be due to the measuring technique in some way, which may be affected by different physiques between genders. This has previously been reported by Girardin et al. [23] and Sadeh and Acebo [19] who claim there is a need for research in both age and sex related activity differences during sleep.

The sleep questionnaire used in this study has been used in a series of laboratory experiments [14,24–26] and has been found to be sensitive to noise effects. The noise levels in this experiments were chosen to be similar to those used in earlier experiments. The study was designed so that all subjects spent the same amount of time in bed at home and in the laboratory, in order to facilitate comparison between nights with different exposures. The subjects had difficulties in following the routine of the study at home in relation to going to bed at the correct time. Their homes were only visited twice, for installation before the first night and collection of playback equipment after night six. Timers controlled the equipment and no staff visited their homes to check that they went to bed at the correct time as the subjects might have felt this was intrusive. Since the difference in time duration in bed was only marginal between home and laboratory nights, this will not affect the possibility to compare the results in the two situations. To avoid expectations no information was given about the exposure conditions; one phone call was made to the subject after the first night with noise, to check that the timers had functioned properly.

8.2. Effects of different types of noise exposure

Judged sleep quality was decreased by 22% after nights with exposure to road traffic noise in the laboratory. This is similar to what Öhrström [14] and Öhrström and Rylander [26] found. In these series of experiment, all with equal number of noise events (64 passing vehicles) and with $L_{A\,max}$ 45 dB and $L_{A\,eq}$ 27 dB, reduction of sleep quality was 18%. In a series with $L_{A\,max}$ 50 dB and $L_{A\,eq}$ 31 dB, sleep quality was decreased with 26% and in another experiment, with $L_{A\,max}$ 60 dB and $L_{A\,eq}$ 38 dB, sleep quality was reduced with 38%. Our result is in line with the earlier experiments and gives a proper dose–response relation between judged sleep quality and $L_{A\,max}$ levels. The combined noise from ventilation and road traffic caused more awakenings; worse sleep quality (−25%) and more movements measured by questionnaire. None of these significant results was detected with actigraphs. The reason why the combined exposure did not affect judged sleep quality more than exposure to traffic noise alone is probably explained by the fact that the combined noise had a more even and therefore less arousing character. It is well known and has previously been shown that an intermittent and fluctuating noise such as road traffic noise disturbs sleep more than an even noise [14,25]. Surprisingly, the results of this study show that the subjects slept better during exposure to ventilation noise, compared to the quiet night, when sleep was measured with actigraphy. The number of wake episodes was significantly decreased; the numbers of sleep episodes increased and the mean sleep episodes were on average 66 min longer. On the other hand, sleep quality assessed by questionnaires was reduced (−12% compared with the quiet night) after the night with exposure to ventilation noise. We could not show any effect on sleep latency or judged minutes to falling asleep from ventilation noise exposure.

Previous sleep studies in the laboratory showed a lower rate of extroversion measured by mood questionnaire after traffic noise exposure during sleep [25].

In the present study, mood was somewhat lower for a few of the variables after all three noise conditions, which supports the effect on sleep shown in the results from judged sleep. However, the differences in mood were small and not entirely easy to interpret since different mood variables showed changes after the different exposures.

Results obtained in the home showed similar, but somewhat stronger effects of road traffic noise than those obtained in the laboratory setting, both for actigraphy and questionnaire assessed sleep variables. In the home, comparing the quiet night with traffic noise exposure, a higher score for activity mean and fewer sleep minutes was found measured with actigraphy, whereas no difference was found between the quiet night and traffic noise exposure in the laboratory. At home, the results from the questionnaire showed a longer time to fall asleep, a reduction in sleep quality by 20.5%, more movements during sleep and the subjects felt more tired in the morning. About the same results were demonstrated for judged sleep quality in the laboratory (−22%) but no other judged sleep variables showed a difference.

As regards the mood questionnaire, the results point in the same direction. In the home, the results showed a lower degree of the mood variables activity, hedonic, socially oriented and secure in the morning after traffic exposure, whereas only one mood variable (relaxed) was affected in the laboratory.

8.3. Sleep at home and in the laboratory during the same exposure conditions

Previous findings by Öhrström showed that after two habituation nights in the laboratory no significant differences could be seen between judged sleep quality at home and in the laboratory [24]. Nor in the present study could differences be found between the two quiet reference nights in the home and in the laboratory measured with actigraph, and judged sleep quality was also equal at home and in the laboratory. This could, at least partly be due to the laboratory being furnished as a home environment and the bedrooms were experienced as cosy. If the environment had been more typical of a laboratory, sleep would probably have been worse than in the home environment.

There was no indication of worse sleep in the laboratory than in the home when subjects were exposed to road traffic noise. Judged sleep quality and mood was equal and, contrary to what was expected, sleep measured by actigraphy seemed to be somewhat better in the laboratory than in the home (shorter sleep latency and mean wake episodes and longer sleep minutes). Effects of road traffic noise on judged sleep quality in laboratory and field studies showed fairly good agreement of difficulties in falling asleep and judged sleep quality, while awakening reactions were much less frequently reported in the field studies [27].

Our study elucidates effects on sleep of acute noise exposure in the home and in the laboratory. The subjects live in rather quiet residential areas and are thus used to lower noise levels than those exposures used in these studies. For comparison of results obtained in home environments among people who have lived in noisy conditions for a long period of time with results obtained in laboratory experiments, more studies are needed. In a second series of sleep studies (ongoing), subjects who live along a busy street with their bedroom windows facing the street are exposed to their "home noise" in the laboratory.

8.4. Sleep assessed by actigraphy and by questionnaires

The results obtained by questionnaires seem more reliable than results obtained by actigraphy since they point in the same direction, e.g., reduced sleep quality after exposure to noise in both the laboratory and home situation. The effects on sleep obtained by questionnaires and by actigraphy were contradictory. Judged sleep quality decreased after exposure to ventilation noise, while sleep assessed by actigraphy indicated an improvement in sleep (more minutes of sleep and fewer wake episodes). Another contradictory result was that according to actigraph-assessed variables, men had worse sleep than women; a result that was not confirmed by the results on sleep variables assessed by questionnaire. These contradictory findings are somewhat surprising since correlations between judged sleep variables and actigraph variables were significant in several cases, e.g., sleep latency and awakenings, which seems reasonable from a logical point of view. A significant correlation between reported awakenings and large body movements has also been found in previous studies, e.g., Öhrström [14]. On the other hand, judged sleep quality was not significantly correlated with any of the actigraphy variables and perceived tiredness in the morning was negatively significantly correlated with all actigraphy variables. The results may be less reliable because actigraphy cannot differentiate between when the subject is awake and immovable or asleep. A previous study found that actigraphy tends to overestimate sleep in comparison to PSG [28] and it has been shown that actigraphy has lower validity if the monitoring time consists only of the bedtime period [18].

9. Conclusions and comments

Traffic noise is more disturbing for sleep quality than ventilation noise at exposure levels used in this study. It thus seems to be better to place a dwelling's bedroom towards the courtyard even if there is ventilation equipment in the courtyard. This is a better solution than locating the bedroom towards a busy road.

The results indicate that laboratory experiments do not exaggerate effects of noise on sleep and that it is possible to compare sleep studies in the laboratory and field. However, new studies are needed where subjects who live in a relatively noisy home environment are exposed to the same noise in the laboratory as in their home environment.

The effects on sleep obtained by questionnaires and by actigraphy were contradictory and the results obtained by questionnaires seem more reliable since they point in the same direction, e.g., reduced sleep quality after exposure to noise in both laboratory and home situation.

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