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Noise emitted from road, rail and air traffic and their effects on sleep

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Abstract

This study compared the effects of road, rail, and aircraft noise and tested the applicability of the equivalent noise level for the evaluation of sleep disturbances. Sixteen women and 16 men (19–28 years) slept during 3 consecutive weeks in the laboratory. Eight persons slept in quiet throughout. Twenty-four persons were exposed to road, rail, or aircraft noise with weekly permuted changes. Each week consisted of a random sequence of a quiet night (32 dBA) and 3 nights with equivalent noise levels of 39, 44, and 50 dBA and maximum levels of 50–62, 56–68, and 62–74 dBA, respectively. The polysomnogram was recorded during all nights, sleep quality was assessed and performance tests were completed in the morning. Subjectively evaluated sleep quality decreased and reaction time increased gradually with noise levels, whereas most physiological variables revealed the same reactions to both the lower and considerably stronger reactions to the highest noise load. Aircraft noise, rail and road traffic noise caused similar after-effects but physiological sleep parameters were most severely affected by rail noise. The equivalent noise level seems to be a suitable predictor for subjectively evaluated sleep quality but not for physiological sleep disturbances.

1. Introduction

Sleep is an essential behaviour that provides physical and mental restoration and sleep disturbances that are considered deleterious to mood, performance, and health. Transportation noise has become a major source of sleep disturbances and this situation will worsen with increasing traffic density within the forthcoming years and here more during the night than during the day.

Integrated noise metrics, such as the equivalent noise level (L_{eq}), the day–night level, or the day–evening–night level are thought to predict sufficiently the effects of transportation noise on residents [1]. But the underlying concept of energy equivalence is debated, at least in view of a meta-analysis which, based on 55 social surveys with overall about 58 000 interviews, has clearly shown that aircraft annoys most and rail noise the least, whereas road traffic noise has an intermediate position [2,3]. These findings support the bonus-malus-regulations that are established in several countries and that allow higher equivalent noise levels for rail than for road traffic noise.

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The concept of energy equivalence is particularly debated among sleep researchers. Whereas the probability of event-related awakenings and body movements clearly increase with the maximum level, integrated noise metrics fail to predict sufficiently the effects of noise from air-, rail or road traffic on sleep (e.g. Refs. [4–6]).

The brain is able to perceive, to analyse and to respond adequately to acoustic stimuli even during sleep and individuals have been shown to react more to meaningful than to neutral stimuli [7,8]. It was therefore hypothesized that human responses to transportation noise during sleep correspond to daytime annoyance.

The aim of this study was first to test this hypothesis and second to test the applicability of the equivalent noise level for the prediction of sleep disturbances. This was done experimentally with 32 participants, each of whom slept during 3 consecutive weeks a 4-day sequence each week in the laboratory. They were exposed with weekly permuted changes to air-, rail and road traffic noise of the same equivalent noise levels, the same maximum levels and the same patterns over night while physiological, subjective and performance data were recorded.

2. Material and methods

2.1. Participants

Thirty-two healthy persons (16 women, 16 men, 19–28 years) participated and gave their written consent to the study which was approved by the local Ethics Committee. They visited the institute 9–11 days prior to the experiment. They were then familiarized with the procedure and completed a training session on performance tests.

2.2. Experimental design

After a habituation night from Sunday to Monday, the participants slept in 3 consecutive weeks during 4 consecutive nights each (Monday–Friday) in the laboratory. The control group (4 women, 4 men) slept under quiet conditions throughout all nights. The experimental group (12 women, 12 men) slept with weekly permuted changes under the influence of air-, rail and road traffic noise, respectively. The 4 nights of each week consisted of a permuted sequence of a quiet and 3 noisy nights with 3 equivalent noise levels.

2.3. Experimental procedure

The participants arrived at the laboratory at about 2100 h where the electrodes for the registration of the polysomnogram were fixed. After the completion of the performance tests, the participants judged the actual situation using a short questionnaire and then went to bed. At 2300 h light was extinguished, noise application and the registration of the physiological data were started. The participants slept in separate sound-proof rooms with air temperature being adjusted to 20 °C. After waking up at 0700 h, sleep quality and fatigue were judged using short questionnaires. Then performance tests were completed.

2.4. Traffic noises

Noises were applied via loudspeakers. As the effects of noise emitted from air, rail, and road traffic noise were to be compared on the basis of the equivalent noise level, other acoustic parameters were kept constant as far as possible. A 32-dBA pink noise was continuously presented during all nights (even during quiet nights) to mask uneven noises from air conditioning and to achieve the same background level in all the 4 experimental chambers. In the noisy nights either aircraft, rail or road traffic noises were added to this background to achieve equivalent noise levels (L_{eq}) of 39, 44, and 50 dBA, where the maximum levels varied from 50 to 62, 56 to 68, and 62 to 74 dBA, respectively. The three types of noises were applied with the same pattern, i.e. with levels decreasing from 2300 to 0100 h and again increasing from 0400 to 0700 h in the morning. The equivalent noise levels actually measured are presented in Table 1. The fact that the equivalent noise levels (not the maximum levels) were somewhat higher for rail noise required some additional calculations (see Sections 3 and 4).

Table 1
Equivalent noise levels and maximum levels during the nights related to the type of noise

Type of noise	Number of events per night	Measures of night-time noise exposure					
		$L_{\mathrm{Aeq},\ 8\,\mathrm{h}}$	L_{Amax}	$L_{\mathrm{Aeq},\ 8\,\mathrm{h}}$	L_{Amax}	$L_{\mathrm{Aeq},\ 8\,\mathrm{h}}$	L_{Amax}
Aircraft noise	195	38.9	46.1–65.4	44.2	51.9–71.1	49.7	57.8–77.1
Road noise	261	38.0	46.1–59.7	43.0	51.9–65.9	49.6	58.3–74.0
Railway noise	172	39.7	45.3–62.3	44.4	51.0–67.8	50.3	57.6–74.1

2.5. Recording and evaluation of dependant variables

2.5.1. Polysomnogram

The polysomnogram (2 EEG, 2 EOG, 1 EMG) was continuously recorded throughout the nights and evaluated according to international recommendations [9]. Each of two experienced evaluators with an excellent inter-rater reliability ($>90\%$ [10]) rated the nights of 16 participants, balanced according to gender and experimental conditions. The nights of each participant were scored in a random order. The parameters derived from each polysomnogram were sleep latency, sleep period time (SPT), wakefulness after sleep onset (WASO), total sleep time ($\mathrm{TST} = \mathrm{SPT} - \mathrm{WASO}$), sleep efficiency index ($\mathrm{SEI} = \mathrm{TST}/\mathrm{SPT}$) and the sleep stages S0 (awake), S1, S2, S3, S4, and rapid-eye-movement (REM), separately for SPT and for the first sleep cycle.

As S0 and S1 (awake and transition from awake to sleep) always changed into the same direction, these parameters were combined and treated as S0&1. S2, which usually amounts about 50%, remained unaffected over SPT and was therefore not listed. Due to a negligible amount of S4 in some participants S3 and S4 were, as in other studies, combined to SWS (slow-wave-sleep, deep sleep).

2.5.2. Subjective evaluation

In the evenings, the participants evaluated their actual situation and actual health condition in short questionnaires. In the mornings they judged their sleep. Using 6 ten-point scales (ranging from 0 to 10) they were requested (‘Please estimate your sleep’) to estimate their difficulties in falling asleep (very easy–very difficult), calmness of sleep (very calm–very restless), sleep depth (very sound–very shallow), sleep duration (very long–very short), restoration (very high–very low), body movements (very little–very much). According to a factor analysis, all these scales loaded on a single factor and were summed up and subtracted from the maximum achievable number (60) and the result was labelled as ‘Sleep quality’. Another ten-point scale was used to estimate actual fatigue (alert–tired).

2.5.3. Performance tests

Two performance tests were completed each evening and morning using personal computers.

Go/Nogo-test: In the simple version, the words ‘drück’ (press) and ‘stopp’ (stop) each showed up 60 times in the centre of the screen for 170 ms in a randomized order. The participants were asked to press a key only in case the word ‘drück’ appeared. In the complex version both words appeared, written in lower and in upper case 50 times each randomly and the participants were advised to respond only to ‘drück’ and ‘STOPP’ but not to ‘DRÜCK’ and ‘stopp’. The inter-stimulus interval was 1750 ms.

Switch-test: A two-figured number showed up for 170 ms in a corner of a virtual square that surrounded a fixed point (small circle) in the centre of a screen. For numbers occurring above or below the virtual horizontal middle line, the position of the even figure or of the greater figure, respectively, had to be indicated using two correspondingly arranged keys. As the overall 240 numbers were presented clockwise, the participants could prepare for the following task (non-switch/switch). The reaction-stimulus interval was 1000 ms.

Reaction times and error rates were calculated for both tests separately, in case of the switch test again separately for the non-switch and for the switch tasks. As error rates in neither of the tests nor the reaction times in the Go/Nogo-test revealed any relation to noise, these data are not presented.

2.5.4. *Statistics*

The Wilcoxon two-sample test was calculated for differences between quiet and noisy nights of the experimental group as well as for the comparison between experimental and control group. Friedman's test for repeated measurements was used to test the overall effect between levels and types of noise (within-subject comparison). Correlations between physiological sleep variables, subjective judgements, and performance data were calculated with linear regression models. p-values $\leqslant 0.05$ were considered significant, p-values$\leqslant 0.10$ indicate a trend. All analyses were performed with SAS 9 for Windows.

3. Results

3.1. *Control vs. experimental group*

None of the variables recorded during or after the 3 quiet nights of the experimental group differed from those of the control group. But the inter-individual comparison between the quiet nights of the control group and the noisy nights of the experimental group indicated worse sleep under the impact of noise, though significance or a trend were ascertained only for the prolongation of latency to SWS (22.4 vs. 14.6 min, $p = 0.04$), a reduction of TST (415.9 vs. 431.9 min, $p = 0.03$) and a decrease of SWS during the first sleep cycle (32.8 vs. 40.1 min, $p = 0.09$). Sleep quality was evaluated worse (31.9 vs. 37.1, $p = 0.02$) whereas performance showed no alterations.

Table 2
Global effects of noise on physiological sleep parameters, subjective evaluation of sleep, and task performance measures of the experimental group

Dependent variables	Quiet nights AM±SD	Noisy nights AM±SD	Noisy–quiet AM±SD	Level of significance
Physiological sleep parameters (min)				
Sleep latency	21.8±12.7	23.7±11.0	1.9±7.9	+
SPT (sleep period time)	455.3±19.6	454.6±10.6	−0.7±16.6	
Latency to slow wave sleep	17.7±9.5	22.4±15.2	4.7±13.2	***
WASO (waketime after sleep onset)	30.0±13.4	38.7±16.2	8.7±11.1	***
TST (total sleep time)	425.3±23.5	415.9±21.9	−9.4±15.6	***
SEI (sleep efficiency, TST/SPT)	0.93±0.03	0.91±0.04	−0.02±0.02	***
Duration of sleep stages during sleep period time				
S0&1 (time awake and in stage S1)	49.2±17.4	62.2±21.3	13.0±14.8	***
SWS (slow wave sleep)	73.3±25.6	67.9±26.2	−5.3±11.0	*
REM-sleep	107.0±14.2	100.6±15.5	−6.4±11.8	*
Duration of sleep stages related to the 1st sleep cycle				
S0&1 (time awake and in stage S1)	9.2±8.2	13.0±11.8	3.8±7.6	**
SWS (slow wave sleep)	35.7±16.9	32.8±14.3	−2.9±8.6	+
REM-sleep	11.4±4.3	12.5±3.9	1.1±3.9	
Subjective evaluation of sleep quality and fatigue				
Subjective sleep quality	38.3±4.8	31.9±5.4	−6.5±5.0	***
Fatigue	4.3±1.8	5.0±1.5	0.8±1.1	***
Reaction times for repeated (non-switch) and for altered (switch) tasks				
Non-switch (ms)	365.4±47.4	369.5±47.7	4.1±11.4	+
Switch (ms)	370.6±49.0	374.4±50.4	3.8±10.0	+

Comparison between 3 quiet nights and 9 nights with noise exposure (with no distinction as to level and to type of noise). Arithmetic means (AM), standard deviations (SD), and levels of significance: $p \leqslant 0.1$: +; $p \leqslant 0.05$: *; $p \leqslant 0.01$: **; $p \leqslant 0.001$: ***; 24 participants; Wilcoxon two-sample test.

3.2. *Within-subject comparisons (quiet vs. noisy nights of the experimental group)*

3.2.1. *Global noise effects*

Within-subject comparisons between the data ascertained during noisy and the quiet night of the experimental group are shown in Table 2, according to which noisy nights differed considerably from quiet nights. SWS was reached later (+4.7 min), WASO was increased (+8.7 min), whereas TST (−9.4 min) and sleep efficiency (−0.02) were decreased. Related to SPT the amount of S0&1 was increased (+13 min), whereas REM-sleep and SWS were decreased significantly (−11.7 min). During the first sleep cycle, the participants spent more time in S0&1 (+3.8 min) and there was a trend towards a decrease of SWS (−2.9 min). Sleep quality was judged worse, participants felt more tired and reaction times for both non-switch and switch tasks showed a trend to prolongation.

3.2.2. *Noise levels*

Table 3 presents means and standard deviations for each noise level and the *p*-values for the differences between quiet and noisy nights of the experimental group. Fig. 1 shows WASO, SWS, REM-sleep and SEI. Apart from sleep latency, from SPT and from REM-sleep during the first sleep cycle, all the other variables altered during noisy nights into the hypothesized direction even at the lowest level ($L_{\text{Aeq}} = 39\,\text{dB}$) but significance ($p \leqslant 0.05$) was only reached for latency to SWS, WASO, SEI, and S0&1 related to SPT. Gradual alterations with noise levels were, as previously hypothesized, only found for the total time spent in SWS and

Table 3
Effects of noise levels on physiological sleep parameters, subjective evaluation of sleep, and task performance measures of the experimental group

Dependent variables	Equivalent noise levels					
	$L_{\text{Aeq}} = 39\,\text{dBA}$		$L_{\text{Aeq}} = 44\,\text{dBA}$		$L_{\text{Aeq}} = 50\,\text{dBA}$	
	AM±SD	Q:39	AM±SD	Q:44	AM±SD	Q:50
Physiological sleep parameters (min)						
Sleep latency	23.3±12.8		24.5±14.9		23.5±12.1	
SPT (sleep period time)	455.3±14.2		454.4±14.8		455.0±12.0	
Latency to slow wave sleep	22.5±17.0	*	19.5±9.6		24.6±22.4	***
WASO (waketime after sleep onset)	36.5±17.1	**	36.0±17.8	*	41.7±20.2	***
TST (total sleep time)	418.8±24.3		418.4±27.0		413.2±25.8	**
SEI (sleep efficiency, TST/SPT)	0.92±0.04	**	0.92±0.04		0.91±0.05	***
Duration of sleep stages during sleep period time						
S0&1 (time awake and in stage S1)	58.4±24.5	**	59.4±23.3	**	66.5±22.4	***
SWS (slow wave sleep)	69.6±29.1		68.0±26.0	*	66.0±26.1	
REM-sleep	102.2±16.3		100.6±19.9		99.4±16.9	**
Duration of sleep stages related to the first sleep cycle						
S0&1 (time awake and in stage S1)	14.3±19.8		10.6±8.4		13.6±9.3	**
SWS (slow wave sleep)	34.0±14.8		33.8±14.8		30.9±15.5	*
REM-sleep	12.0±5.3		11.3±4.9		13.9±5.0	*
Subjective evaluation of sleep quality and fatigue						
Subjective sleep quality	34.4±6.6	***	32.8±5.7	***	28.5±6.8	***
Fatigue	4.5±1.6		5.0±1.7	***	5.6±1.8	***
Reaction times for repeated (non-switch) and for altered (switch) tasks						
Non-switch (ms)	366.7±50.0		369.6±47.2	*	372.2±47.7	**
Switch (ms)	371.2±50.4		375.1±50.9		376.9±51.9	**

Comparison between nights with noise exposure (with no distinction as to type of noise) and quiet nights (Q, see Table 2). Arithmetic means (AM), standard deviations (SD), and levels of significance: $p \leqslant 0.05$: *; $p \leqslant 0.01$: **; $p \leqslant 0.001$: ***; 24 participants; Wilcoxon two-sample test.

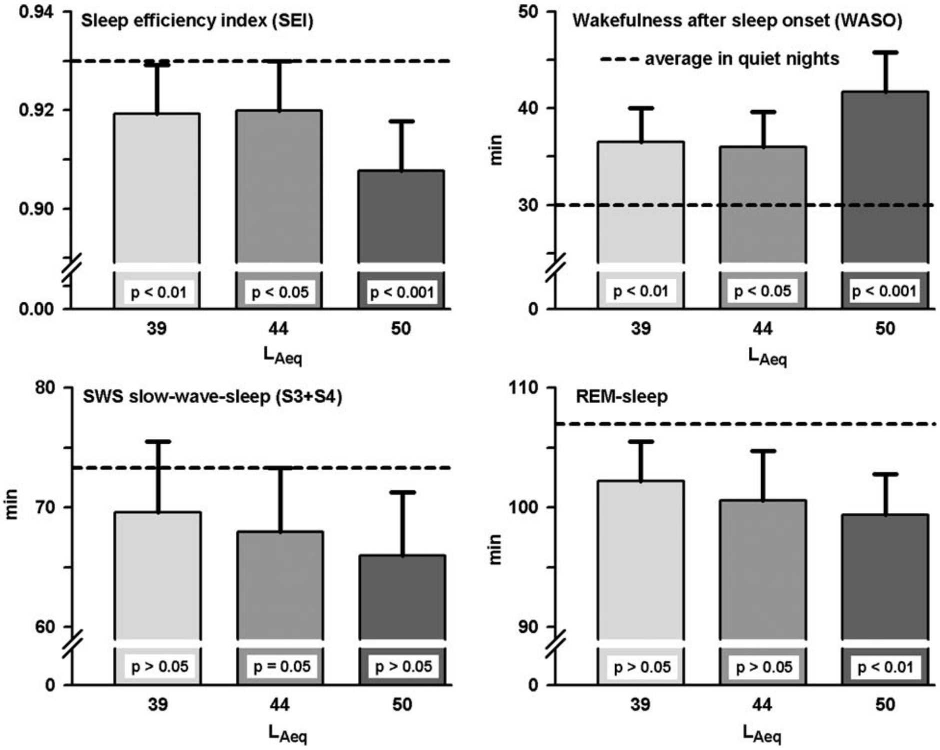

Fig. 1. Effects of noise levels on selected physiological sleep parameters. Means (boxes) and standard errors (bars) during noisy nights as compared to means ascertained during quiet nights (broken line). Twenty-four participants; 19–28 years; Wilcoxon-two-sample test; p: levels of significance.

in REM-sleep (related to SPT). The other variables showed similar effects under the noise loads of 39 and 44 dBA but a much stronger reaction to $L_{eq} = 50$ dBA. The Friedman test did not show significant differences between the three levels.

Fig. 2 presents sleep quality, fatigue and reaction times observed in the switch test, all of which altered gradually with noise load in a dose–response manner. Sleep quality decreased and fatigue increased. Reaction times increased gradually but reached significance only after the loudest nights.

3.2.3. Types of traffic noise

Table 4 shows means and standard deviations for each type of noise and for the p-values for the effects of noise types. Fig. 3 shows latency to SWS, the total time spent in SWS as well as the time of SWS and of S0&1 during the first sleep cycle. Most physiological sleep variables showed the strongest impairment under the impact of rail noise and the smallest under the impact of road traffic noise but significance was reached only for latency to SWS, for the total time spent in SWS as well as for S0&1 and SWS during the first sleep cycle.

Sleep quality was significantly reduced and fatigue was increased, irrespective of the type of noise, to the same extent.

As rail noise was somewhat louder than aircraft and road traffic noise, the averages of all the physiological, the subjective and the performance data ascertained during or after the noisy nights were averaged for rail noise over the two lower noise levels and compared to the averages calculated over the two higher levels of aircraft and road traffic noise. The results remained stable, indicating stronger responses to rail noise.

3.2.4. Correlations

Correlations, presented in Table 5, were calculated between physiological data, subjective sleep quality and performance. Due to the number of data (24 participants × 12 nights), the level of significance was set to

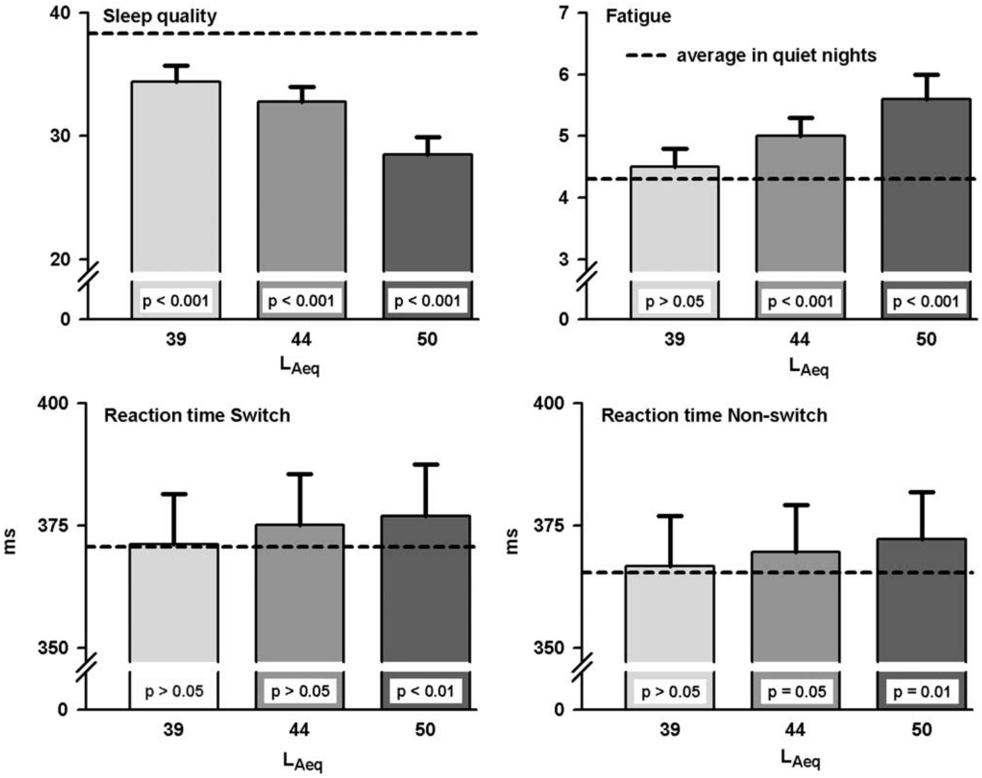

Fig. 2. Effects of noise levels on subjective sleep quality, fatigue, and reaction time in the switch test after noisy nights. Means (boxes) and standard errors (bars) during noisy nights as compared to means ascertained after quiet nights (broken line). Twenty-four participants; 19–28 years; Wilcoxon-two-sample test; *p*: levels of significance.

$p \leqslant 0.01$. Thereafter sleep quality decreased with increasing sleep latency and latency to SWS and increasing WASO, with decreasing TST and SEI, with increasing amount of S0&1 and decreasing time spent in REM-sleep.

Reaction times for non-switch and switch tasks increased significantly with latency to SWS and the time spent in S0&1 during the first sleep cycle and with a decreasing time spent in SWS during the first sleep cycle as well as during the entire night (related to SPT).

4. Discussion

4.1. Methods

4.1.1. Polysomnography

During the last 2 decades, sleep disturbances were often indicated by body movements, which are easier to record and much easier to evaluate than the polysomnogram [5,6,11,12]. But actigrams do not provide information about sleep depth and cannot reliably detect awakenings. So, this study relied on the polysomnogram which was recorded and evaluated according to internationally accepted criteria [9].

4.1.2. Subjective evaluation of sleep

The questionnaire for subjective evaluation of sleep is certainly a reliable instrument, as the results are confirmed by the findings of other authors [13,14], in particular by the association between sleep quality and sleep latency, TST, the time spent in S0&1 and the difficulty to fall asleep (indicated by the prolonged latency of SWS).

Table 4
Effects of type of traffic noise on physiological sleep parameters, subjective evaluation of sleep, and task performance measures of the experimental group

Dependent variables	Type of traffic noise						
	Aircraft (A)		Road (R)		Rail (T)		
	AM ± SD	Q:A	AM ± SD	Q:R	AM ± SD	Q:T	A:R:T
Physiological sleep parameters (min)							
Sleep latency	21.3 ± 7.7		25.2 ± 14.3		24.1 ± 17.0		
SPT (sleep period time)	457.2 ± 7.7		452.8 ± 14.3		454.1 ± 16.6		
Latency to slow wave sleep	23.2 ± 19.3	***	19.6 ± 13.6		24.6 ± 16.4	***	*
WASO (waketime after sleep onset)	38.4 ± 19.0	**	36.2 ± 16.2	**	42.0 ± 21.7	***	
TST (total sleep time)	418.8 ± 21.4		416.6 ± 25.7	**	412.1 ± 31.3	***	
SEI (sleep efficiency, TST/SPT)	0.93 ± 0.04	**	0.92 ± 0.04	**	0.91 ± 0.05	***	
Duration of sleep stages during sleep period time							
S0&1 (time awake and in stage S1)	62.5 ± 22.4	***	58.4 ± 19.8	**	66.3 ± 30.1	***	
SWS (slow wave sleep)	70.8 ± 27.7		68.7 ± 26.7	*	64.6 ± 26.5	**	**
REM-sleep	101.4 ± 16.7		103.1 ± 16.5		97.5 ± 20.0	**	
Duration of sleep stages related to the first sleep cycle							
S0&1 (time awake and in stage S1)	12.8 ± 12.6	**	9.8 ± 7.1		16.3 ± 17.6	***	*
SWS (slow wave sleep)	33.5 ± 14.3		39.9 ± 15.8		29.1 ± 15.4	**	*
REM-sleep	13.8 ± 6.3		12.7 ± 5.1		11.4 ± 4.8		
Subjective evaluation of sleep quality and fatigue							
Subjective sleep quality	32.1 ± 6.2	***	32.5 ± 7.1	***	31.0 ± 5.5	***	
Fatigue	5.0 ± 1.7	*	5.0 ± 1.8	**	5.1 ± 1.5	***	
Reaction times for repeated (non-switch) and for altered (switch) tasks							
Non-switch (ms)	367.0 ± 46.2		372.8 ± 52.3		368.7 ± 52.3		
Switch (ms)	372.1 ± 48.1		375.7 ± 54.2		375.4 ± 56.7		

Comparison between nights with noise exposure (with no distinction as to level of noise) and quiet nights (Q, see Table 2). Arithmetic means (AM), standard deviations (SD), and levels of significance: $p \leqslant 0.05$: *; $p \leqslant 0.01$: **; $p \leqslant 0.001$: ***; 24 participants; Wilcoxon two-sample test; Friedman's test for the comparison between aircraft, rail and road traffic noise.

4.1.3. Performance

Performance decrements after noisy nights were reported by only a few authors [13,15,16]. The lack of impairments in most studies (e.g. Refs. [4–6,17]) might be related to the tests usually applied (simple reaction time tests, 3- or 4-choice tests) which are not sensitive enough to be affected by sleep disturbances as usually evoked by noise. This study focussed on executive functions which originate in the frontal lobe of the brain and which are prone even to partial sleep deprivation [18,19]. Accordingly, reaction times for non-switch and for switch tasks increased gradually with noise load. The correlation between reaction times and the time spent in SWS suggests a model according to which work speed is causally related via a shortened SWS to the impact of noise during sleep. This suits the findings of Born and Plihal [20] who have reported a reduction of declarative memory performance after retention of SWS. The present results indicate that executive functions are sensitive to even minor sleep disturbances [19].

4.2. Effects of noise

4.2.1. Control group vs. experimental group

Though the data ascertained during the quiet nights of the experimental and the control group did not differ, the inter-individual comparison between the noisy nights of the experimental group and the quiet nights of the control group were less significant than the intra-individual differences between

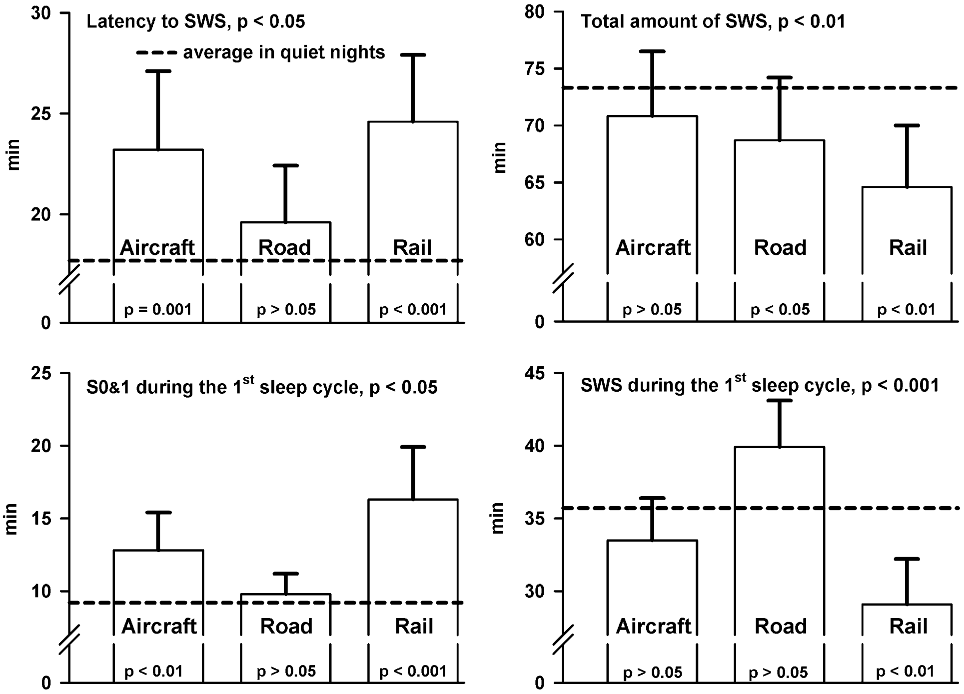

Fig. 3. Effects of the type of noise on selected physiological sleep parameters. Means (boxes) and standard errors (bars) during noisy nights as compared to means ascertained during quiet nights (broken line). Twenty-four participants; 19–28 years; Wilcoxon-two-sample test; p: levels of significance.

Table 5
Significant correlation coefficients ($p \leqslant 0.01$) of physiological sleep parameters with task performance measures and with subjective evaluation of sleep of the experimental group

	Subjective sleep quality	Reaction time (ms)	
		Switch	Non-switch
Physiological sleep parameters			
Sleep latency	−0.23***		
SPT (sleep period time)	0.20***		
Latency to slow wave sleep (SWS)	−0.31***	0.29**	0.29**
WASO (waketime after sleep onset)	−0.21***		
TST (total sleep time)	0.27***		
SEI (sleep efficiency, TST/SPT)	0.22***		
Duration of sleep stages during sleep period time			
S0&1 (time awake and in stage S1)	−0.29**		
SWS (slow wave sleep)		−0.38**	−0.38**
REM-sleep	0.26**		
Duration of sleep stages during the first sleep cycle			
S0&1 (time awake and in stage S1)	−0.24**	0.28**	0.29**
SWS (slow wave sleep)		−0.33**	−0.33**

Calculations based on the 12 individual nights of 24 participants ($n = 288$). Levels of significance: $p \leqslant 0.01$: **; $p \leqslant 0.001$: ***.

the noisy and the quiet nights of the experimental group. This discrepancy is, however, certainly related to the small number of control persons and the unbalanced size of both groups (8 control vs. 24 experimental persons).

4.2.2. Global noise effects within the experimental group

The findings are generally in line with the literature but in contrast to some studies, where either REM-sleep or SWS decreased [17,21,22], both these sleep stages were reduced here, at a total of 12 min. This might be explained by the noise pattern applied here, which was characterized by high levels in the early night, when SWS prevails, and again in the early morning, when REM-sleep dominates.

4.2.3. Noise levels

The total time spent in SWS and in REM-sleep decreased gradually with the acoustic load, where the other physiologic variables showed almost the same alteration to both the lower levels ($L_{\mathrm{eq}} = 39$, 44 dBA) and a considerably stronger response to $L_{\mathrm{eq}} = 50$ dBA which might indicate a threshold for differences of at least 6 dBA. The assumption of a small resolving power is supported by the studies of Basner et al. [4] who observed a surprisingly small increase of sleep disturbances with the increase of the maximum and the equivalent noise levels, respectively, and first awakening reactions when the maximum levels exceeded the background level by 6 dBA.

The lack of a gradual increase of physiologically indicated sleep disturbances with the equivalent noise level is supported by the literature according to which integrated noise metrics are not suitable for the prediction of sleep disturbances, whereas event-related awakenings or body movements clearly increase with the maximum levels [4,6].

Subjective sleep quality decreased and fatigue increased gradually and significantly with noise levels suggesting that the equivalent noise levels are suitable for the prediction of the after-effects, i.e. the subjective evaluation of the whole night. This conclusion is supported by extended laboratory studies (e.g. Ref. [21]), where persons were observed under different acoustic situations [13,23,24] or by field studies when the acoustic conditions were abruptly altered, e.g. by insulating windows, by the installation of tunnels or by the opening of newly constructed roads [25–28]. In contrast, however, comparisons between residents exposed to different noise loads scarcely revealed similar dose–response relations, probably due to the fact that these reactions are prone to habituation [5,6].

4.2.4. Type of traffic noise

The hypothesis adopted for this study bases firstly on the replicated observation that man responds more likely to meaningful than to neutral noises even during sleep [7,8] and secondly on a meta-analysis according to which aircraft noise annoys most and rail noise the least [2,3]. A correspondingly differentiated response was expected here, namely the strongest response to aircraft noise and the smallest to rail noise. This hypothesis, was, however, not verified. Most sleep parameters, subjective evaluation of sleep, and performance did not differentiate between the three types of noise. Only latency to SWS, the total time spent in SWS as well as in S0&1 and in SWS during the first sleep cycle showed an effect of the type of noise. But contrary to expectation, the largest effects occurred under the influence of rail noise whereas aircraft and road traffic noise caused smaller alterations. The stronger effect to rail noise remained when both the lower noise levels of rail noise were compared to both the higher noise levels of aircraft and of rail noise.

To date, very few studies concerned the effects of different traffic noises on sleep. Vernet [29] performed a field study where road traffic noise disturbed, probably due to the greater number of events, more than rail noise of the same equivalent noise level. Another field study was performed with 377 residents, who were mainly exposed to rail or to road traffic noise and observed over 2 × 5 consecutive nights. But neither body movements nor subjective assessment or performance revealed different responses to the two types of noises, though extensive interviews of the same persons revealed a considerable ‘bonus’ for rail noise [5]. Eventually, rather limited laboratory experiments on event-related responses to the three types of noises revealed the strongest reaction to rail noise, even though the maximum levels were lower than those of aircraft noise [22,30]. This might firstly be related to the shorter rise times of rail noises, to which the organism usually reacts more than to slowly rising levels or to steady states [31], and secondly to the longer lasting periods of relatively high levels along with the characteristic temporal structure of rail noise.

5. Conclusions

The present study compared the effects of noises emitted from aircraft, rail and road traffic which were applied with the same equivalent noise levels, the same maximum levels and the same patterns during the night. With increasing noise levels, gradually increasing alterations were determined for the after effects, i.e. for subjective assessment and performance, whereas, apart from SWS and REM-sleep, the physiological variables showed the same reactions to both the lower but considerably stronger reactions to the highest noise load. Thus the equivalent noise level seems to be a suitable predictor for subjective evaluation but not for the physiological disturbances of sleep.

Concerning the type of noise most variables did not show any differences, but latency to and the amount of SWS (deep sleep) which are decisive for restoration were—contrary to expectation—more affected by rail noise than by aircraft and by road traffic noise.

Several countries, e.g. the Federal Republic of Germany allow higher noise levels along railway tracks than on roads. This 'bonus' bases on extended social surveys whereafter aircraft noise annoys most and rail noise the least, which was most clearly shown by the meta-analysis performed by Miedema and co-workers [2,3]. This bonus is also supported by Hygge [32] who examined performance during exposure to the three traffic noises (presented with the same equivalent noise levels and the same maximum levels) and found the least impairment under the impact of rail noise. The present results, that are supported by a few other studies, lead to the question, whether this bonus is also valid for a completely different stage of consciousness, namely for sleep. It is, however, premature to suggest a modification or a cancellation of the bonus during night time. Such far-reaching decisions require the confirmation of the present results on the basis of various noise scenarios, in particular, as the scenarios applied here were rather artificial. Replication is needed with more realistic scenarios.

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