Science of the Total Environment 424 (2012) 48–56

Contents lists available at SciVerse ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Examining nocturnal railway noise and aircraft noise in the field: Sleep, psychomotor performance, and annoyance☆,☆☆

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ARTICLE INFO

Article history:
Received 29 November 2011
Received in revised form 9 February 2012
Accepted 14 February 2012
Available online 21 March 2012

Keywords:
Railway noise
Aircraft noise
Awakening reaction
Sleep
PVT
Annoyance

ABSTRACT

Background: Traffic noise is interfering during day- and nighttime causing distress and adverse physiological reactions in large parts of the population. Railway noise proved less annoying than aircraft noise in surveys which were the bases for a so called 5 dB railway bonus regarding noise protection in many European countries.
Objectives: The present field study investigated railway noise-induced awakenings during sleep, nighttime annoyance and the impact on performance the following day. Comparing these results with those from a field study on aircraft noise allowed for a ranking of traffic modes concerning physiological and psychological reactions.
Methods: 33 participants (mean age 36.2 years ± 10.3 (SD); 22 females) living alongside railway tracks around Cologne/Bonn (Germany) were polysomnographically investigated. These data were pooled with data from a field study on aircraft noise (61 subjects) directly comparing the effects of railway and aircraft noise in one random subject effects logistic regression model. Annoyance was rated in the morning evaluating the previous night.
Results: Probability of sleep stage changes to wake/S1 from railway noise increased significantly from 6.5% at 35 dB(A) to 20.5% at 80 dB(A) LAFmax. Rise time of noise events had a significant impact on awakening probability. Nocturnal railway noise led to significantly higher awakening probabilities than aircraft noise, partly explained by the different rise times, whereas the order was inversed for annoyance. Freight train noise compared to passenger train noise proved to have the most impact on awakening probability. Nocturnal railway noise had no effect on psychomotor vigilance.
Conclusions: Nocturnal freight train noise exposure in Germany was associated with increased awakening probabilities exceeding those for aircraft noise and contrasting the findings of many annoyance surveys and annoyance ratings of our study. During nighttime a bonus for railway noise seems not appropriate.

1. Introduction

Traffic noise is intrusive in multiple aspects of everyday life with consequences for physical and psychological health of affected residents (Muzet, 2007; World Health Organization (WHO), 2011). During the day people feel distressed and annoyed concerning efficiency of working, learning, communication or recreation (Evans et al., 1995; Haines et al., 2001, 2002; Hygge et al., 2002; Stansfeld et al., 2005; Stansfeld and Matheson, 2003). During the night traffic noise causes disturbances of the physiological sleep process which are assumed to be the most severe primary effects of noise (World Health Organization (WHO), 2009; World Health Organization (WHO), 2011), and which may lead to secondary reactions the following day like fatigue, performance impairments and annoyance reactions (Elmenhorst et al., 2010; Marks and Griefahn, 2007). Beyond that links to long-term effects are discussed like an increased risk for cardiovascular disease (Babisch, 2006; Jarup et al., 2008; Selander et al., 2009).

Rail traffic is one of the major means of transportation for goods. Despite the economical crisis of the last years, the German freight traffic volume has increased by 3.1% in 2010 compared to 2009. Regarding the development of freight traffic in Germany as reported by the German Federal Statistical Office from the years 2002 until 2010,

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☆ Parts of this work concerning the impact of railway noise were published in Quehl J, Müller U, Maass H, Pennig S, Rolny V, Basner M, Elmenhorst EM: “Dosis-Wirkungsbeziehungen aus einer Feldstudie zur Wirkung nächtlichen Bahnlärms auf den Schlaf, die psychomotorische Leistung und die Belästigung”, Lärmbekämpfung 6(5), 188–196, 2011.

☆☆ Disclosures: Dr. Basner is Associate Editor of the journal SLEEP. Dr. Basner has received compensation for consulting from Purdue University for the FAA PARTNER Center of Excellence Project 25B. Dr. Basner has made paid presentations to the World Health Organization (WHO, German office). The other authors declare no conflict of interest.

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doi:10.1016/j.scitotenv.2012.02.024

freight transported via rail increased by 25% (from 285.4 million tons to 355.4 million tons) and via air traffic nearly doubled (from 2.2 million tons to 4.1 million tons). Moreover, Germany serves as transit country for freight transportation between different European destinations. Research, however, has focused mainly on the impact of road traffic and aircraft noise in the past years, based on the assumption that if railway noise is less annoying (Miedema and Oudshoorn, 2001; Miedema and Vos, 1998), it has probably also less negative physiological effects. Based on these and similar results of studies that found a decrease of annoyance in the order aircraft, road traffic, and rail traffic noise (so called "Miedema curves"), average rail traffic noise is allowed to be 5 dB higher than road or aircraft noise in several countries (e.g. Germany) before noise protection has to be installed. A recent study conducted in six European countries has reported that annoyance especially due to aircraft noise has even increased in the last years in comparison to "Miedema curves" during daytime as well as during nighttime while annoyance due to road traffic noise remained the same (Babisch et al., 2009). In contrast to results of predominantly European surveys (European Commission Working Group on Health and Socio-Economic Aspects, 2004; Miedema and Vos, 2007), railway noise is known to be more annoying respectively sleep disturbing than road traffic noise in Asian countries (Hong et al., 2010). Distinctions in the basic structure of buildings and the closeness to railway tracks might explain some of the observed differences between Asian and European countries.

Several recent investigations indicate that railway noise also leads to significant sleep fragmentation and cardiovascular activations during sleep (Griefahn et al., 2006; Marks and Griefahn, 2005; Saremi et al., 2008; Tassi et al., 2010), and to subjective distress (Lercher et al., 2010).

Recently, we conducted a laboratory study which compared the impact of air, road, and rail traffic noise on annoyance and polysomnographically assessed sleep structure in a systematic approach. Results have indicated a major impact of railway noise on sleep. In opposition to the feeling of annoyance, sleep fragmentation increased in the order air, road, and rail traffic noise (Basner et al., 2011).

Although laboratory experiments offer the advantage of a controlled environment, it is often found that effects of noise on sleep, annoyance, and performance are stronger and therefore easily overestimated in laboratory settings (Elmenhorst et al., 2010; Fidell et al., 1995; Horne et al., 1994; Pearsons et al., 1995; Quehl and Basner, 2006). Laboratory findings should therefore always be validated in field experiments. The present study was conducted in order to obtain exposure–response relationships for railway noise exposure and awakening reactions during sleep, annoyance during nighttime, and performance the following day in the field. In the years 2001 and 2002, we performed a similar field study on aircraft noise so that a direct comparison of the exposure–response relationships was possible as well as a ranking concerning the impact on sleep, annoyance, and performance. To our knowledge, this paper provides for the first time a ranking of polysomnographically assessed awakening reactions during sleep due to railway and aircraft noise.

2. Methods

2.1. Study subjects

We examined 33 subjects aged between 22 and 68 years (mean age 36.2 years ± 10.3 SD) in their homes regarding their nighttime railway noise exposure; 22 participants were female. Subjects were recruited in regions near Cologne and Bonn (Germany) along the river Rhine where settlements are close to railway tracks and freight traffic runs predominantly at night. The mean duration of residence was 5.5 years (± 6.0 SD) covering a range of 0.7 to 29.6 years.

Subjects were selected in a multi-level selection process: questionnaires screened for physical, psychological, sleep or circadian disorders. A medical examination made sure that subjects were in good physical health, that they did not suffer from intrinsic sleep disorders, and that they had a normal hearing threshold according to their age. In one night prior to the study we recorded the nocturnal traffic noise to ensure that our subjects were primarily exposed to railway noise with only minor exposure to other noise sources.

All subjects signed an informed consent according to the Declaration of Helsinki and were reimbursed for participation. The study was approved by the Ethics Committee of the North Rhine Medical Board.

2.2. Design and acoustics

Each subject was examined during nine consecutive nights. Study periods always began on Monday. Subjects were free to choose their bedtime individually, but they had to keep a minimal bedtime of at least six hours per night between midnight and 6 am, and had to get up latest at 8 am.

Noise events and levels were recorded during the night at the sleeper's ear using class-1-sound level meters (NC10, Cortex Instruments). A noise event was defined as an increase in sound pressure that exceeded L90 by 3 dB(A). The maximum sound pressure level of a noise event was defined as the highest point of the sound event curve. The rise time of a noise event is represented by the steepest slope of the noise event curve. Human scorers identified noise sources by listening to the noise events. In addition, a 1-min time span directly preceding the start of a noise event was determined in order to show by how far this "1-min background LAeq" as a marker of the current background noise level was exceeded by the noise event. The A-weighted energy equivalent noise level (LAeq) at the sleeper's ear was calculated for subject's individual time in bed. Recordings took place at 27 different homes resulting in 241 nights recorded and analysed in total (two nights were excluded because of a defect in the sound level meter; $9 \times 27 = 243$ nights). During these nights, in times when subjects stayed in bed, we registered 11836 events from freight trains and 4193 events from passenger trains. The number of freight trains per night ranged from 1 to 150 and of passenger trains from 0 to 42 (Fig. 1). The descriptive results of the main acoustical exposure variables are displayed in Table 1.

2.3. Polysomnography

We recorded subjects' polysomnograms including the electroencephalograms (EEG: C4, F4, O2, A1, A2), the electrooculograms (EOG), the electromyograms (EMG), the electrocardiograms (ECG), respiratory movements of thorax and abdomen, and finger pulses. Sleep epochs were analysed according to the criteria of R&K (Rechtschaffen et al., 1968) and EEG arousals were classified corresponding to the guidelines of the American Sleep Disorders Association (Bonnet et al., 1992). Electrophysiological signals and acoustical data were sampled synchronously with the same time base. A detailed description of the event-related noise-sleep analyses is presented in Basner et al. (2008). Furthermore, sleep latencies were calculated as markers of disturbances during the process of falling asleep; i.e. time elapsed between going to sleep and the occurrence of the first sleep stage S1 was defined as sleep onset latency (SOL), and the first occurrence of deep sleep or REM sleep after sleep onset was classified as SWS-latency or REM-latency, respectively. Sleep efficiency was defined as the amount of sleep without wake periods (total sleep time) in the sleep period (sleep period time = SPT).

2.4. Psychological variables

In the morning shortly after awakening subjects filled in questionnaires concerning annoyance due to nocturnal railway noise, subjectively perceived awakenings, sleep quality, sleep quantity, sleep latency, and problems falling asleep. Annoyance from railway noise during the night

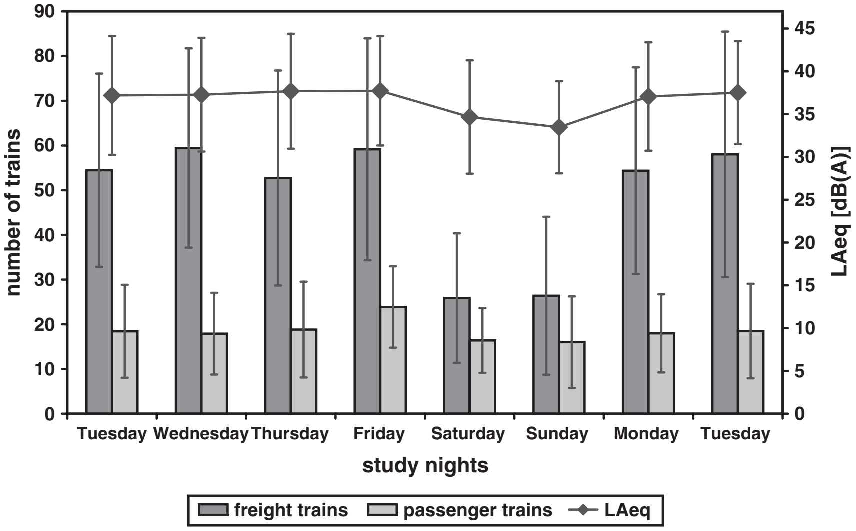

Fig. 1. Distribution of the noise load throughout the study. LAeq = energy equivalent noise level; noise levels at the sleeper's ear.

was rated on a five-point scale ("1 = not" to "5 = very" annoyed) according to recommendations of the International Commission on Biological Effects of Noise (ICBEN) (Fields et al., 2001). Different from the "Miedema curves" our annoyance questions were only concerned with the short-term annoyance perceived in the previous night. Subjective sleep quality included depth of sleep, calmness of sleep, difficulties in falling asleep, sleep duration, body movements, and recuperation during sleep (Griefahn et al., 2006). Non-acoustic moderators of annoyance were taken into account; i.e. personal moderators (e.g. annoyance from railway noise prior to the study, subjective adaptation, noise sensitivity, length of residence, age, gender), and social moderators (e.g. attitude towards rail traffic: necessity, accident risk, health effects).

2.5. Psychomotor performance

Psychomotor performance was measured in the morning shortly after awakening and in the evening not long before bedtime, using a computer-assisted 10-min psychomotor vigilance task (PVT) that was implemented on the test software ERTS (experimental run time system) of the Berisoft Company (Frankfurt, Germany). The trigger signal was a white digital stopwatch appearing in intervals of between 1.5 s to 10 s at the dark screen that had to be responded to by pressing a predefined key as fast as possible. Reaction times that lasted 500 ms or longer were regarded as lapses (Dinges and Powell, 1985), whereas reaction times that were shorter than 130 ms were registered as reactions without stimulus (false starts). Subjects were trained 24 times in conducting the test prior to the start of the study to guarantee stable baseline performance.

Table 1
Descriptive results of the acoustical data.

Variable	Range	Median	25th perc.	75th perc.
Distance homes from tracks [m]	13 to 96	32	25	56
Number of freight trains	1 to 150	48	28	64
Number of passenger trains	0 to 42	17	11	25
Duration of freight train noise events [s]	32 to 227	64	50	85
Duration of passenger train noise events [s]	15 to 79	29	24	38
LAFmax [dB(A)]	23.4 to 81.3	49.0	41.7	58.1
LAeq [dB(A)]	23.1 to 50.9	37.1	32.2	40.9
1-min background LAeq [dB(A)]	16.6 to 63.0	26.7	22.4	32.0
Difference of LAFmax from 1-min background LAeq [dB(A)]	0.0 to 58.5	18.1	11.7	25.2
Sound pressure rise time [dB(A)/s]	0.3 to 9.0	3.0	1.6	4.4

Noise levels at the sleeper's ear.

2.6. Statistics

The present paper focuses on the development of exposure–response relationships between railway noise and the outcome variables of sleep, psychology, and performance. The first night of the study served as adaptation to the measuring equipment and was excluded from analyses. Event-related analyses of noise and awakenings/sleep stage changes from any deeper sleep stage to S1 (in the following referred to as awakenings), and analyses of overall noise load during the night and its effects on annoyance, were computed using random intercept mixed logistic regression models (R 2.12.1, package glmmML). Since the highest category 5 was not rated in the present sample, annoyance was transformed in a dichotomous variable (1 + 2 = 0 = low annoyance and 3 + 4 = 1 = high annoyance). Sleep latencies, sleep efficiency, and mean reaction times in PVT were analysed with mixed model regressions using a random intercept model (PROC MIXED, SAS 9.2). Lapses and false starts in PVT were so rare that again exposure–response relationships were calculated using random intercept logistic regression models (absence of lapses/false starts = 0, at least one lapse/false start = 1).

In a second step, data of the present study were pooled with data from a field study on the effects of aircraft noise including 61 subjects (Basner et al., 2006; Elmenhorst et al., 2010; Quehl and Basner, 2006) forming a single data set. Selection of variables for modelling was carried out automatically in a stepwise selection procedure (Fahrmeir et al., 2007); i.e. starting from a simple intercept model, variables were tested separately and in combinations until the best model possible was generated according to the Akaike Information Criterion (AIC) (Pinheiro and Bates, 2009). A model based on a pooled data set was better suited to explain differences between the effects of railway and aircraft noise than the comparison of two separate models. Differences between traffic modes were further analysed in calculating interactions.

The following acoustical parameters were taken into account: energy equivalent noise level (LAeq) during bedtime, which is calculated by integrating the sound energy of all noise events in the time given, number of noise events during bedtime, duration of noise events during bedtime, maximum sound pressure level (LAmax) of the single noise event, difference of LAmax from the 1-min background LAeq, sound pressure level rise time. LAmax was calculated using the fast time constant (LAFmax) for analyses of the impact of railway noise. As a conjoint basis for comparing railway and aircraft noise effects LAmax was calculated using the slow time constant (LASmax).

Significance level was assumed at $\alpha<0.05$. If not otherwise mentioned values in the text are given as mean ± standard deviation.

3. Results

3.1. Railway noise and sleep

During weekdays subjects spent on average 441 min (±40 min) in bed, whereas mean bedtime on weekends (nights: Friday to Saturday and Saturday to Sunday) was 45 min longer (486 min ± 63 min). Sleep efficiency throughout the study nights averaged 89.5% (±6.2%) (weekdays: 89.3 ± 6.6%, weekends: 89.1 ± 7.6%). SOL averaged 16 min (±11 min), SWS-latency 40 min (±52 min), and REM-latency 77 min (±26 min) on weekdays compared to 15 min (±12 min), 42 min (±45 min), and 74 min (±25 min) on weekends, respectively. Neither sleep efficiency ($p>0.72$) nor sleep latencies ($p>0.12$) showed any significant relation to the nocturnal railway noise exposure.

For event-related analyses of railway noise events and corresponding awakenings, 8866 railway noise events were available that were undisturbed from any other noise sources in a time window of 60 s prior to the noise event until 90 s after the noise event began. LAmax of noise events is widely used for interpreting traffic noise exposure. We noted that in our sample the difference of LAFmax of the noise event from the 1-min background LAeq (Table 2) fitted the data slightly better than the use of the variable LAFmax per se (Table 3). However, both models show nearly identical values. Awakening probability for railway noise events increased significantly from 7.7% at 5 dB(A) to 13.1% at 50 dB(A) LAFmax difference from 1-min background LAeq, or from 6.5% at 35 dB(A) to 20.5% at 80 dB(A) LAFmax. Sound pressure rise time (LAFmax rise time) of the noise event was a highly significant predictor for awakenings as well. The probability for awakenings increased significantly with elapsed sleep time. The probability decreased with prolonged noise events. The linear and quadratic coefficients of time elapsed in the same sleep stage before the noise event occurred reflect an increased probability to wake up if the sleep stage has just been changed. This probability decreased with time elapsed in the current sleep stage and increases again with time past. The probability for awakenings was calculated in comparison to the probability to awake from the most prevalent sleep stage S2. It was decreased for deep sleep (S3, S4), but increased slightly for REM sleep. Awakening probability did not show differences in gender, but increased with age. The best fit was chosen according to the AIC (Pinheiro and Bates, 2009). Fig. 2 shows the awakening probability depending on the difference of LAFmax from the 1-min background LAeq. The corresponding graph displaying the awakening probability depending on LAFmax is presented in Fig. 3.

Table 2
Random intercept multivariate logistic regression model concerning the relation of railway noise events and the probability of sleep stage changes to awake/S1.

Variable	Regression coefficient (standard error)	z-value	p-value
Intercept	−3.1317 (0.2942)	−10.64	<0.0001
Difference of LAFmax from 1-min background LAeq	0.0131 (0.0049)	2.66	0.0078
LAFmax rise time	0.0516 (0.0103)	4.99	<0.0001
Duration of noise event	−0.0043 (0.0015)	−2.90	0.0038
Elapsed sleep time	0.0007 (0.0002)	4.28	<0.0001
Age	0.0181 (0.0066)	2.74	0.0062
Gender	0.0323 (0.1421)	0.23	0.8200
Elapsed time in same sleep stage	−0.0345 (0.0048)	−7.21	<0.0001
Elapsed time in same sleep stage ^{2}	0.0003 (0.0000)	6.33	<0.0001
Sleep stage S3	−1.0406 (0.3172)	−3.28	0.0010
Sleep stage S4	−0.4231 (0.4062)	−1.04	0.2970
REM sleep	0.1341 (0.0897)	1.50	0.1350

Gender: male = 1, LAFmax = maximum sound pressure, noise levels at the sleeper's ear.

Table 3
Random intercept multivariate logistic regression model concerning the relation of railway noise events and the probability of sleep stage changes to awake/S1.

Variable	Regression coefficient (standard error)	z-value	p-value
Intercept	−4.0161 (0.3550)	−11.31	<0.0001
LAFmax	0.0291 (0.0060)	4.85	<0.0001
LAFmax rise time	0.0410 (0.0105)	3.89	<0.0001
Duration of noise events	−0.0047 (0.0015)	−3.22	0.0013
Elapsed sleep time	0.0006 (0.0002))	3.99	<0.0001
Age	0.0132 (0.0069)	1.93	0.0539
Gender	0.0311 (0.1440)	0.22	0.829
Elapsed time in same sleep stage	−0.0334 (0.0047)	−7.16	<0.0001
Elapsed time in same sleep stage ^{2}	0.0003 (0.0001)	6.24	<0.0001
Sleep stage S3	−1.0578 (0.3169)	−3.34	0.0008
Sleep stage S4	−0.3927 (0.4036)	−0.97	0.331
REM sleep	0.1638 (0.0888)	1.84	0.0651

Gender: male = 1; noise levels at the sleeper's ear.

3.2. Comparing railway and aircraft noise effects on sleep

For event-related analyses 8866 undisturbed railway noise events (6749 freight train noise events and 2117 passenger train noise events) and 10658 undisturbed events of aircraft noise were available. The model is presented in Table 4. An interaction between maximum sound pressure level and traffic mode was included in the model to distinguish between effects caused by different traffic modes; i.e. freight trains, passenger trains and airplanes. Most interestingly, for equal levels of LASmax the awakening probability decreased in the order freight train noise, aircraft noise, and passenger train noise. For LASmax values of ≥51 dB(A) awakening probability from freight train noise events exceeded that from aircraft noise events; i.e. at LASmax of 75 dB(A) awakening probability from freight train noise was 7% higher than from aircraft noise (Fig. 4).

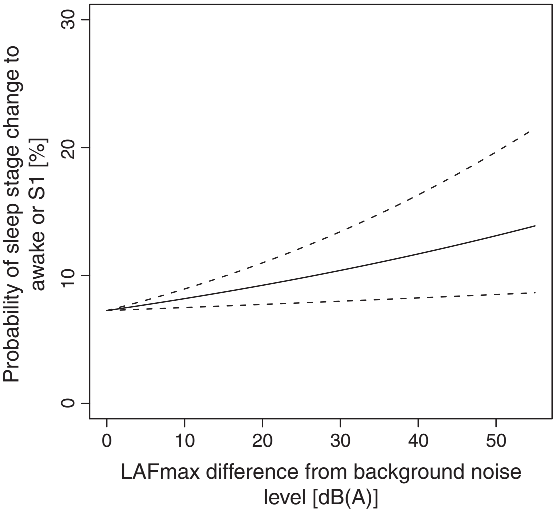

Fig. 2. Probability for sleep stage changes to awake and S1 depending on the difference of the maximum sound pressure of a railway noise event from the 1-min background LAeq. Exposure–response relationship and 95% confidence interval base on a random effects multivariate logistic regression model. Assumptions: prior sleep stage = S2, elapsed sleep time = 601 (middle of the second half of the night), duration of the noise event = 58 dB(A)/s (median), elapsed sleep time in the same sleep stage before the noise event began = 14 epochs (median), sound pressure rise time = 3 dB(A)/s (median), age = 34 years (median), gender = male; noise levels at the sleeper's ear.

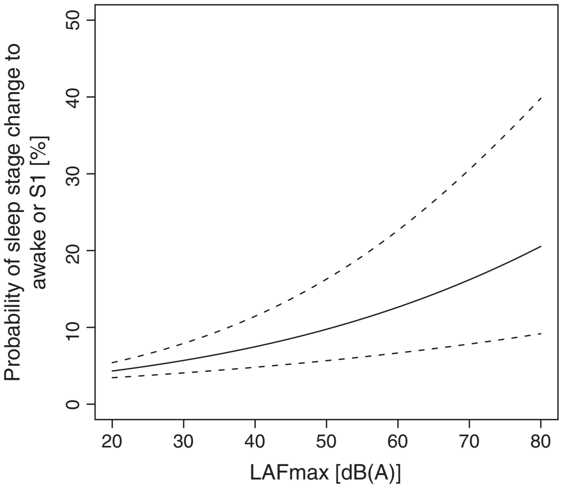

Fig. 3. Probability for sleep stage changes to awake and S1 depending on the maximum sound pressure of a railway noise event. Exposure–response relationship and 95% confidence interval base on a random effects multivariate logistic regression model presented in Table 4. Assumptions: prior sleep stage = S2, elapsed sleep time = 601 (middle of the second half of the night), duration of the noise event = 58 dB(A)/s (median), elapsed sleep time in the same sleep stage before the noise event began = 14 epochs (median), sound pressure rise time = 3 dB(A)/s (median), age = 34 years (median), gender = male; noise levels at the sleeper's ear.

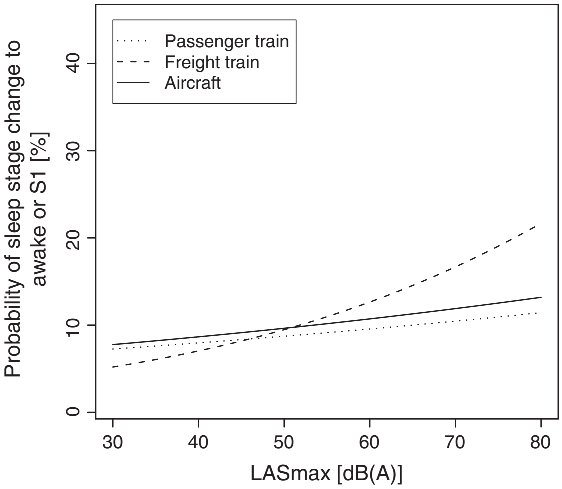

Fig. 4. Ranking of the probability for sleep stage changes to awake and S1 due to freight train, passenger train and aircraft noise depending on the maximum sound pressure level of the noise event. Exposure–response relationships base on a random effects multivariate logistic regression model presented in Table 5. Assumptions: prior sleep stage = S2, elapsed sleep time = 601 (middle of the second half of the night), elapsed sleep time in the same sleep stage before the noise event began = 11 epochs (median), 1-min background LAeq = 20.7 dB(A) (median), sound pressure rise time depending on the sound pressure level by linear regression, age = 34 years (median), gender = male; noise levels at the sleeper's ear.

3.3. Railway noise and subjective assessment of sleep disturbances

Subjective rating of SOL averaged 19 min (±13 min), and 22% of subjects complaint about problems during the process of falling asleep. Subjects remembered nightly awakenings in 79% of study nights; 20% of these awakenings were noted to be caused by railway noise. Subjects reported problems of falling asleep again after an awakening in 17% of nights; in 40% of these nights subjects indicated that railway noise was the reason for these problems. Only subjectively reported awakenings during the night showed a significant relation to the nocturnal noise exposure. The probability for awakenings increased with rise in LAeq by trend (0.019 ± 0.011 SE, p = 0.094), with number of railway noise events in general (0.004 ± 0.002 SE, p = 0.024), and with number of freight train noise events (0.004 ± 0.002, p = 0.021). Passenger train noise did not significantly affect reported awakenings (0.005 ± 0.008, p = 0.528). Subjective sleep latency, problems of falling asleep, subjectively rated sleep quantity, sleep quality, sleep depth, calmness of sleep, and recuperation did not show any significant relation to the nocturnal railway noise exposure.

Table 4
Random intercept multivariate logistic regression model concerning the relation of freight train, passenger train and aircraft noise events and the probability of sleep stage changes to awake/S1.

Variable	Regression coefficient (standard error)	z-value	p-value
Intercept	−3.4737 (0.2723)	−12.76	<0.0001
LASmax (aircraft noise)	0.0112 (0.0049)	2.28	0.0228
LASmax * passenger train noise	−0.0108 (0.0117)	−0.92	0.357
LASmax * freight train noise	0.0151 (0.0077)	1.97	0.0490
LASmax rise time (aircraft noise)	0.0386 (0.0090)	4.30	<0.0001
LASmax rise time * passenger train noise	0.0300 (0.0273)	1.10	0.271
LASmax rise time * freight train noise	0.0074 (0.0143)	0.52	0.605
Passenger train noise (indicator variable)	0.2511 (0.5013)	0.50	0.616
Freight train noise (indicator variable)	−0.8163 (0.3667)	−2.23	0.0260
1-min background LAeq	0.0051 (0.0072)	0.70	0.482
Elapsed sleep time	0.0007 (0.0001)	6.63	<0.0001
Elapsed time in same sleep stage	−0.0241 (0.0034)	−7.19	<0.0001
Elapsed time in same sleep stage ^{2}	0.0003 (0.0000)	6.25	<0.0001
Sleep stage S3	−0.6934 (0.1330)	−5.22	<0.0001
Sleep stage S4	−0.5312 (0.2099)	−2.53	0.0114
REM sleep	0.2960 (0.0572)	5.18	<0.0001
Age	0.0081 (0.0035)	2.31	0.0209
Gender	−0.0283 (0.0854)	−0.33	0.740

Gender: male = 1, LASmax = maximum sound pressure; noise levels at the sleeper's ear.
Due to the interaction term of the parameter LASmax, the real coefficient for passenger train respective freight train has to be calculated as the sum of the estimated coefficient for aircraft noise (0.0112 LASmax (aircraft)) plus the estimated interaction coefficient of passenger train (0.0112 + (−0.0108) = 0.0004) respective of freight train (0.0112 + 0.0151 = 0.0263).

3.4. Comparing railway and aircraft noise effects on annoyance

None of the acoustic parameters alone (LAeq and number of noise events) showed significant effects on annoyance from railway noise evaluating the previous night. Non-acoustic variables were included in the model and in a stepwise backward procedure (eliminating non-acoustic moderators with highest p-values from the model) the non-acoustic moderators "subjective adaptation to railway noise" and "duration of residence" were identified having a significant influence on annoyance. When testing these non-acoustic moderators with acoustic parameters in a regression model, only number of noise events (p = 0.018) showed significant effects on annoyance (subjective adaptation: p = <0.001, duration of residence: p = 0.015). Therefore, number of nocturnal railway noise events was selected for comparison with effects of aircraft noise. Results of the regression model (Table 5) indicated that nocturnal aircraft noise was more annoying than nocturnal railway noise (Fig. 5) though statistically not significant. Annoyance ratings were independent from gender but increased with age.

3.5. Railway noise and cognitive performance

Mean reaction time in morning PVT averaged 252.3 ms (±28.8 ms) on weekdays and 249.9 ms (±29.3 ms) on weekends. In the evening test, mean reaction time was faster and averaged 242.0 ms (±28.3 ms) on weekdays compared to 241.6 ms (±28.5 ms) on weekends. Mean reaction time and lapses in PVT did not show any significant relation to the

Table 5
Random intercept multivariate logistic regression model concerning the relation of number of railway and aircraft noise events during the night and annoyance.

Variable	Regression coefficient (standard error)	z-value	p-value
Intercept	−6.9577 (1.0868)	−6.40	<0.0001
Number of events (aircraft noise)	0.0374 (0.0080)	4.68	<0.0001
Number of events * Railway noise	−0.0183 (0.0137)	−1.34	0.181
Railway noise (indicator variable)	0.6260 (0.8550)	0.73	0.464
Age	0.0719 (0.0204)	3.52	0.0004
Gender	−0.5392 (0.4821)	−1.12	0.263

Gender: male = 1; noise levels at the sleeper's ear.
Due to the interaction term of the parameter number of events, the real coefficient for railway has to be calculated as the sum of the estimated coefficient for aircraft noise (0.0374 number of events (aircraft)) plus the estimated interaction coefficient of railway noise (0.0374 + (−0.0183) = 0.0191).

Table 6
Statistical results of regression analyses concerning the relation between nocturnal railway noise exposure (LAeq) and performance on the Psychomotor Vigilance Test (PVT).

		Regression coefficient (standard error)	t-value	p-value
Morning PVT	Mean RT	−0.0648 (0.2447)	−0.26	0.7915
	Lapses	0.0070 (0.0435)	0.16	0.8729
Evening PVT	Mean RT	−0.3386 (0.2589)	−1.31	0.1927
	Lapses	0.0328 (0.0514)	0.64	0.5275

PVT = psychomotor vigilance task. RT = reaction time.

noise exposure during the night, neither in the morning nor in the evening tests (Table 6). Therefore, we did not pool railway and aircraft noise data. More important for performance during the day was the duration of SPT. Reaction time in the morning test improved significantly with 0.03 ms/min SPT (p = 0.0352). Gender did not have a significant influence on mean reaction time and lapses (p > 0.2), but performance decreased significantly with age (mean reaction time: 1.2 ms (± 0.4 ms SF) per year, p < 0.01; lapses: 0.09 (± 0.03 SF) per year, p < 0.05).

4. Discussion

In this study, awakening reactions due to railway noise were for the first time polysomnographically assessed in the field and analysed in an event-related approach. Likewise, impact of railway noise on annoyance, on subjective sleep disturbances during the night, and on performance the next day was obtained. Pooling the data with field data on aircraft noise made a direct comparison between railway noise and aircraft noise possible that allows for a ranking of physiological and psychological reaction probabilities depending on the acoustical load. In comparison to field studies conducted in the past, polysomnography — the "gold-standard" in recording sleep — was used in a subject sample that is large (33 subjects) relative to the methodological expense, and that covers a wide age range (22 to 68 years).

Railway noise did not lead to prolonged sleep latencies or to impaired sleep efficiency compared to normal population values (Ohayon et al., 2004) and did not show significant relations to the noise load received during the night. Macrostructure of sleep (i.e. sleep latencies, amount of sleep stages, and sleep continuity) is known to be seldom significantly altered by noise (Basner et al., 2011; Basner and Samel, 2005; Griefahn et al., 2008a). However, a recent field study on the effects of railway vs. road traffic noise detected impairment in REM sleep associated with railway noise (Aasvang et al., 2011). Even though the latency to fall asleep was quite precisely estimated by the subjects (16 min recorded vs. 19 min estimated) and 22% complained about problems in falling asleep, subjective sleep latency and subjective problems in falling asleep were not significantly related to noise nor were subjective depth, calmness, quality and quantity of sleep. This is in line with field studies that have not shown significant relations of noise on subjective sleep quality and quantity (Griefahn et al., 2000; Horne et al., 1994), whereas laboratory studies on railway noise have reported significant effects (Griefahn et al., 2006; Quehl and Basner, 2008).

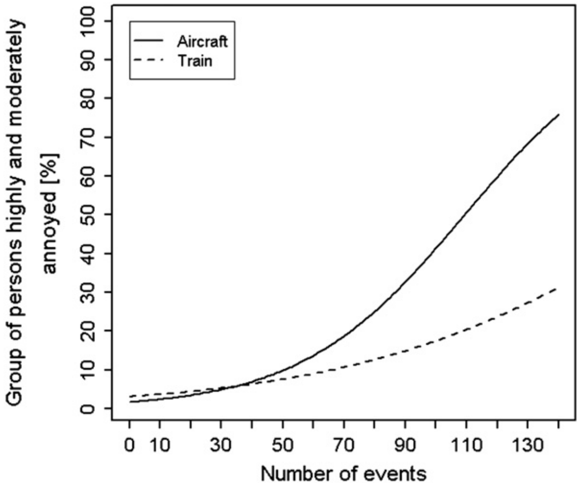

Fig. 5. Comparing railway and aircraft noise effects in the probability to lead to moderate to highly annoyance ratings depending on the number of nocturnal noise events. Assumptions: age = 34 years (median), gender = male; noise levels at the sleeper's ear.

Similar to the effects of noise on macrostructure of sleep, effects on psychomotor performance the following day are mostly small and hardly detectable. Consequently, studies on nocturnal traffic noise and performance have led to contradictory results. Griefahn et al. (2000), Marks and Griefahn (2005) and Schapkin et al. (2006) have not reported impairments in cognitive performance following a night with road, rail, or aircraft noise. Several research groups, however, detected performance decrements in relation to the nocturnal noise load (Öhrstrom, 1995; Öhrstrom and Rylander, 1990; Griefahn and Gros, 1986; Wilkinson and Campbell, 1984). In our studies on aircraft noise, we have observed significant effects on the macrostructure of sleep in a laboratory setting (112 subjects) (Basner and Samel, 2005) leading to small but significant impairments in psychomotor performance the next morning (Elmenhorst et al., 2010). That we did not find performance impairments in this study on railway noise, although using the same performance test (PVT), could be explained by the subject sample that might have been too small and by the sleep durations in the field setting that might have been too irregular in order to overcome subjects' variance in performing the tests. Since performance improved significantly with increased sleep duration, the explanation seems plausible.

Event-related multivariate logistic regression analyses showed that railway noise significantly increased awakening probability reaching a probability of 20.5% at 80 dB(A) LAFmax. The model with the best fit included the difference of the maximum sound pressure level from the 1-min background LAeq instead of the maximum sound pressure level. Awakening probability increased up to 13.1% at 50 dB(A) LAFmax difference from 1-min background LAeq. An early study of Vernet (1979) on railway noise has already hinted at the difference of the maximum sound pressure from the background noise level as important acoustical variable. Basner et al. (2006) have reported increased awakening probabilities if the noise event was only 6 dB louder than the background noise level. The most important recorded noise characteristics to predict awakening reactions proved to be the sound pressure rise time, the maximum sound pressure respective the difference of the maximum sound pressure from the

1-min background LAeq, and the duration of the noise event. The probability to wake up from a noise event is highest in the beginning of the event and decreases with continued duration. The explanation for this observation might be that those subjects with low arousal thresholds wake up early from a noise event. Since sleep pressure decreases exponentially with elapsed sleep time and with deep sleep that is most prominent in the first half of the night, awakening probability increases with elapsed sleep time. In comparison to the light sleep stage S2 awakening probability is low during deep sleep but somewhat increased during REM sleep. An equivalent field study on aircraft noise has reported similar awakening probabilities (Basner et al., 2006).

Consistent with these results subjects remembered awakenings in 79% of study nights and in one fifth of these cases reported railway noise as the cause. Subjective awakenings increased significantly with nocturnal railway noise. If subjects had problems in falling asleep again after an awakening, they reported in 40% of cases that railway noise was the reason for staying awake. Since noise can only be subjectively evaluated in the wake state, we assume that these consciously experienced wake periods during the night that are related to a noise source are the bases for the nocturnal feeling of annoyance. Only the number of noise events had a significant impact on annoyance ratings in a random effects logistic regression model that included subjective adaptation to noise and duration of residence as non-acoustic moderators. Two percent of subjects fell in the annoyance categories 3 and 4 (moderate to rather annoyed) with 10 railway noise events occurring during the night. Increasing the nightly number to 183 rail traffic noise events resulted in 45% of subjects rating these categories. Our results underline the importance of non-acoustic moderators of annoyance as has been stated before (Guski, 1999). As expected, subjects that reported to have problems in adapting to noise reached higher levels of annoyance. But annoyance also increased with duration of residence so that it can be assumed that the two moderators represent independent concepts. Our results therefore clearly argue against a general habituation with long-term noise exposure (Weinstein, 1982). Whether the willingness to cope with railway noise decreases over time or whether we observe an adverse reaction to increased noise exposure remains open. The overall annoyance due to railway noise during the night, retrospectively assessed the next morning, was rather low throughout the study with 2% of subjects rating categories 4 and 5, whereas 54% of subjects reported to be annoyed in these categories due to railway noise before the study began. Since the annoyance query prior to the study was not explicitly related to the nocturnal noise exposure, this result hints at the wake hours as most important times for generating the feeling of annoyance. Higher annoyance ratings during evening hours than during daytime (Schreckenberg et al., 2010) and higher annoyance ratings during daytime than during nighttime (Hoeger et al., 2002) have been reported previously and support our findings. Griefahn et al. (2000) have stated regarding the results of a social survey on railway and road traffic noise that the current acoustical situation when filling in a survey might influence the outcome.

The comparison between nocturnal railway and aircraft noise effects on sleep and annoyance revealed that while aircraft noise led to higher nocturnal annoyance compared to railway noise (non-significant), this order was inversed for awakening probabilities. The probability to wake up due to railway noise was significantly higher and exceeded the awakening probability due to aircraft noise by 7% at 75 dB(A). This finding is astonishing but supported by results from laboratory studies that found the same order of effects on sleep and annoyance in a carefully balanced study design (Basner et al., 2011), and found the same order of effects on sleep after adjusting for an unbalanced study design (Marks et al., 2008). It has been stated that the differing results on the impact of railway noise on annoyance and sleep could be based on the discrepancy between types of trains examined in different studies (Saremi et al., 2008). The results of our study do not support this hypothesis, since the same train by-passes led to the described inverse ranking of annoyance and sleep fragmentation. The findings strengthen the notion that annoyance only occurs if subjects wake up and does not reflect unconscious physiological reactions while asleep. In addition, the differences between annoyance from aircraft and railway noise might be influenced by the time pattern of the nightly exposure. While railway noise was more evenly distributed during the night, most over-flights took place in the beginning (11:00 pm to 1:00 am) and near the end (3:00 am to 5:00 am) of the sleep period. Since disturbances of sleep are regarded as strong adverse effects, our results clearly argue for a revision of the so called "railway bonus" at least during nighttime.

Noise from freight trains caused significantly more awakenings than noise from passenger trains, the latter inducing even less waking reactions than aircraft noise (non-significant difference and only after adjusting for sound pressure rise time). This is critical if freight trains form the greatest part of the nocturnal rail traffic as it was the case in our study. Saremi et al. (2008) have as well reported an increased awakening probability for freight trains in comparison to passenger and automotive trains under a standardized noise and maximum sound pressure pattern. Special characteristics of freight train noise like sharp and fluctuating sounds or the duration of the noise event (though not contributing to improve the fit of the model) may explain some of the difference (Tassi et al., 2010). Part of the difference in awakening probability due to freight train and aircraft noise can be explained by sound pressure rise time. Sound pressure rise time depends on the noise source and may as well be related to the maximum sound pressure level of a noise event. In our sample maximum sound pressure level and sound pressure rise time of aircraft noise were not correlated ($r^2 = 0.045$) whereas these acoustical parameters showed a moderate correlation for railway noise ($r^2 = 0.398$). Maximum sound pressure level and sound pressure rise time increase both with the velocity of a train. Buildings in the neighbourhood might shield the noise emission from railways so that the noise event occurs suddenly with high rise times and maximum sound pressure levels whereas noise from aircraft is audible already from the distance increasing more slowly. Adding sound pressure rise time to the model reduced the difference between railway and aircraft noise considerably. Several recent studies are in line with our findings. Griefahn et al. (2008b) and Basner et al. (2011) have observed accelerations in heart frequency increasing with sound pressure rise time which was especially prominent after railway noise in comparison to road and aircraft noise. Lercher et al. (2010) have judged the sound pressure rise time of train noise events as equally important for predicting motility reactions as the maximum sound pressure level. This underlines the importance to consider sound pressure rise time of noise sources in future noise protection concepts. Our ability to predict the effects of noise will increase, the more we learn about noise characteristics and possible predictors. We showed that rise time in addition to LAmax is a suitable predictor. Both predictors are strongly related to the velocity of freight trains, so that possible noise protection procedures could be to reduce the velocity of freight trains in residential areas, to shield the noise source from the settlements or to modernize trains (e.g. more silent wagons and breaks). It remains to be seen if these recommendations are politically achievable.

4.1. Limitations

Exposure–response relationships that we calculated in the present study are derived from a German subject sample under the influence of nocturnal rail and air traffic. To date, it remains unclear if results can be transferred to other countries or different airports. Freight wagons that are technically outdated or more developed may result in different physiological reaction probabilities.

The ecological validity of this field study is high, and the method of measuring sleep sophisticated, however both factors limited the number of investigated subjects. Especially for psychological measurements larger subject samples can minimize the confidence interval.

Results are derived from a healthy subject sample. We assume that effects are even more pronounced in parts of the population that are at risk; i.e. very young and very old, people suffering from illnesses, sleep disorders, or circadian misalignment.

5. Conclusions

Physiological reactions during sleep due to railway noise cannot be predicted from annoyance queries. At the same noise level, annoyance (evaluating the previous night) is higher due to aircraft noise than due to railway noise, whereas awakening probabilities due to railway noise are higher than due to aircraft noise. Especially freight train by-passes are responsible for awakenings. Sound pressure rise time is one important acoustical factor to explain different awakening probabilities. Noise protection legislation for railway noise should be reviewed at least for nighttime.

Acknowledgements

We are deeply grateful for the subjects' ambition to participate in the study and for the help of our colleagues at the German Aerospace Center in collecting the data. This work represents work package 3 “Sleep disturbances due to traffic noise” of the German–French-cooperation (Deufrako) which was funded by the Federal Ministry of Economics (BMWi) as part of the project “RAPS (Railway Noise — and other modes — Annoyance, Performance, Sleep)”. We thank all our partners for the cooperation.

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