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Noise sensitivity impacts the evaluation of sleep due to vibration and noise from freight trains

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ABSTRACT

Freight trains are expected to increase on the European railway network. Freight trains are particularly problematic with regards to generation of low frequency vibration and noise which has the potential to propagate to nearby homes and influence residents. Sleep is expected to be of critical importance from a health perspective. As part of the EU project Cargovibes, we have carried out three laboratory trials with a total of 59 young healthy persons (28 men and 31 women) over 350 person-nights to ascertain physiological and psychological reactions to nocturnal vibration and noise from freight traffic, and to examine differences between gender and noise sensitivity. Nights with low (0.0058 m/s^2) moderate (0.0102 m/s^2) and high (0.0204 m/s^2) maximum weighted vibration amplitudes and low (20), moderate (36) and high (52) number of train passages were simulated keeping the noise levels of the same order. Sleep was assessed using polysomnography and questionnaires. This paper focusses on the impacts of individual's noise sensitivity on the assessed sleep. Noise sensitive persons reported overall less sleep quality and had a lower amount of slow wave sleep, making them potentially vulnerable to nocturnal disturbances.

Keywords: Noise sensitivity, Vibration, Sleep disturbance

1. INTRODUCTION

Noise sensitivity refers to the internal states of an individual (physiological, psychological, or life-style determined), which increases the degree of reactivity to noise in general [1]. It has been shown to be a moderating factor for transportation noise annoyance [2, 3], and is prevalent among around 22% [2] to 50% [4] of a population. Apart from a greater psychological response, studies also point to a greater psychophysiological response among noise sensitive individuals when exposed to noise [5, 6]. Because of their enhanced reaction to environmental stimuli, noise-sensitive persons might therefore be particularly vulnerable to nocturnal exposure.

As part of the EU funded CargoVibes project, the research group has been investigating the impact on sleep arising from night time vibration and noise exposure from freight trains (for project overview, see [7]). During the course of three laboratory studies involving 59 participants over 350 person-nights

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we have obtained a dataset of physiological and psychological reactions to different exposure scenarios comprising different vibration amplitudes and numbers of events. This large dataset provides us the opportunity to study the impact of individual noise sensitivity on sleep.

2. METHODS

2.1 Participants

For each of the three trials, female and male volunteers aged 18 – 30, were recruited by public advertisement. Exclusion criteria were i. reduced hearing acuity (>20 dB hearing loss at a single frequency as determined via audiometric testing with an Entomed SA 201), ii. BMI <18.5 or ≥25, iii. self-reported snoring, iv. self-reported allergies and/or hypersensitivity and v. being a tobacco user or caffeine dependent. Before attending they were asked about their noise sensitivity on a 5-point Likert scale ("How would you describe your sensitivity to noise? 1. Not at all sensitive, 2. Not particularly sensitive, 3. Somewhat sensitive, 4. Very sensitive, 5. Extremely sensitive. In total 38 persons (19 males, 19 females) rated themselves as being noise insensitive (points 1-2) and 21 (9 males, 12 females) rated themselves being noise sensitive (points 3-5). Although grouping of participants was done according to this question only, other measurements were used for validation: participants of study II were additionally asked for noise sensitivity with the Weinstein questionnaire [8] and participants of study III were asked about their general environmental sensitivity [9]. Comparison between these different measurements showed a good accordance between the single item question and the Weinstein questionnaire ($r=0.47$, $p=0.04$) as well as with the environmental sensitivity questionnaire ($r=0.46$, $p=0.03$). The methods and materials are described in detail elsewhere [10, 11] and only summarised here. The studies were approved by the Ethics Committee of Gothenburg.

2.2 Evaluation of sleep

Polysomnographical (PSG) recordings included electroencephalogram (EEG), electrooculogram (EOG) and submental electromyogram (EMG), breathing, pulse and oxygen saturation. The placement of the electrodes and the PSG analyses were performed in accordance with AASM criteria [12]. Sleep was manually scored in 30s epochs by a qualified sleep technician into sleep stages W (wake), N1, N2, Slow Wave Sleep (SWS) and Rapid Eye Movement (REM). They also identified the start time and duration of EEG arousals classified corresponding to the guidelines of the American Sleep Disorders Association [13]. An arousal of >15s duration was classed as an awakening. PSG data was used to determine sleep onset latency (SOL), defined as the time until the first occurrence of a non-wake epoch. Wakefulness after sleep onset (WASO) is the total time spent in W between SOL and the final awakening. Sleep efficiency is the ratio of the time spent asleep to the total time in bed (480 minutes). A sleep stage change (SSC) is defined as moving from any given sleep stage to a "lighter" stage other than W, with REM being classed as the lightest stage in accordance with Carter et al [14].

Questionnaires were administered each morning immediately following awakening. They included questions on sleep quality, sleep disturbance by vibration, and sleep disturbance by noise, each rated on an 11-point numerical scale. Questions were also posed on how they currently felt, with very rested-very tired, very relaxed- very tense and very irritated- very glad as endpoints. Also included were questions on time to fall asleep and number of times the subject woke up. Other questions on how the subject experienced the night and their sleep included how easy/difficult it was to fall asleep, if the sleep was better or worse than usually and whether it was deep/shallow. At the end were questions on mood [15] and stress/energy [16].

2.3 Laboratory facilities

The sleep laboratory is constructed as an apartment with a separate entrance to which the subjects have their own key. The apartment comprises a kitchen/ living room, bathroom and toilets as well as three rooms furnished as typical bedrooms with a bed, chairs, desk and small chest of drawers. The bedrooms are individually isolated from external noise and vibration. The low frequency content of the noise below 125 Hz is reproduced via 88 ceiling loudspeakers while higher frequencies are generated by two loudspeaker cabinets in the room corners. Because of the low background noise levels in the rooms (<14 dBA), artificial ventilation noise was introduced at a level of 25 dBA at the pillow position for the duration of the experiment.

2.4 Exposures

Eight different exposure scenarios were created over the 3 studies. Based on field measurements, the vibration signal was an amplitude modulated 10 Hz sinusoid, which was input along the length of the bed [17]. The vibration signal was adjusted over different nights to have either a W_d weighted low (0.0058 ms^{-2}), moderate (0.0102 ms^{-2}) or high (0.0204 ms^{-2}) maximum amplitude, measured on the bed frame (slow time filter). Noise exposures were audio recordings of freight trains of different durations, rise times and maximum levels, spectrally filtered to correspond to a closed window (more detailed information available in Smith *et al.* [10]). Experimental nights consisted of 20, 36 or 52 trains. The night time 8-hour vibration data for all exposure conditions is presented in Table 1. All values are W_d weighted according to ISO 2631-1 [18]. Rms was calculated according to Equation 1.

$$a_w = \left[\frac{1}{T}\int_0^T a_w{}^2(t)dt\right]^{\frac{1}{2}} \tag{1}$$

Table 1 Eight-hour ISO-2631 weighted vibration for all experimental nights. Denotations: N=noise exposure, V=vibration exposure, l/m/h=low/moderate/high vibration amplitude, 20/36/52=number of events.

Experimental night	$rms_{d,23\text{-}07}$ (ms^{-2})
N36	-
NVl36	0.0007
NVm20	0.0010
NVm36	0.0014
NVh20	0.0019
Vh36	0.0027
NVh36	0.0027
NVh52	0.0033

2.5 Study design

For each participant, the study consisted of one habituation night and one control night before four experimental nights in which simulated trains passed. The arrangement of the experimental nights was randomised across participants. Care was exercised to spread gender and noise sensitivity approximately equally within the randomised nights.

The participants were instructed to arrive at the sleep laboratory at 20:00 in the evening, go to bed and begin attempting to fall asleep at 23:00 and were woken at 07:00 in by an automated alarm call. Otherwise they could follow their normal daily routine. The participants were not permitted to drink any caffeinated beverages after 15:00 during the experimental week. The PSG equipment was attached between 20:00 and 22:30 and the subjects were then free to move around in the laboratory apartment before going to bed. All volunteers provided informed written consent and were financially reimbursed for their participation.

2.6 Statistical analysis

Subjective data was combined from all three studies and analysed in SPSS v.18 (SPSS Inc., Il., USA) using a mixed effect model with exposure (combined exposure nights vs. control night) and noise sensitivity as fixed effects and the individual participants as random effects. Data was visually inspected for outliers and a single data point (control night, sensitive female) subsequently excluded from "time to fall asleep" because the participant reported a time to fall asleep of >3 hours, which was not supported by the PSG data. PSG data was analysed for the four exposure conditions (i.e. excluding control) from Study II with a univariate ANOVA model for repeated measurements and noise sensitivity as a between-subject effect. The numbers of participants used for calculation of the subjective results across all three trials, and for the PSG data along with corresponding noise sensitivity and gender distribution from a single trial (second study), are presented in Table 2.

Table 2 - Total number of participants within each experimental condition across all 3 studies. Subjective data is from all three studies. PSG data is from a single study and listed by participant noise sensitivity and gender (F=female, M=male).

		Control	N36	Vh36	NVl36	NVm20	NVm36	NVh20	NVh36	NVh52
	Subjective data	N=59	N=34	N=22	N=12	N=24	N=36	N=24	N=58	N=22
PSG (study 2 only)	Noise sensitive, F	N=7	-	-	-	N=7	N=7	N=6	N=7	-
	Noise sensitive, M	N=3	-	-	-	N=3	N=3	N=3	N=3	-
	Non-sensitive, F	N=6	-	-	-	N=6	N=6	N=6	N=6	-
	Non-sensitive, M	N=8	-	-	-	N=8	N=8	N=8	N=8	-
	PSG total	N=24	-	-	-	N=24	N=24	N=24	N=24	-

3. RESULTS

3.1 Subjective data

All questionnaire results for the control and pooled exposure nights for both sensitivity groups are presented in Table 3. Relative to non-sensitive persons, the noise sensitive group reported reduced overall sleep quality (p=0.008, F=7.1, Figure 1) and reduced sleep quality in five of six questions about sleep parameters (Time to fall asleep: p=0.026, F=5.0; number of wakeups: p<0.001, F= 13.4; Deep sleep-light sleep: n.s.; Easy to sleep-difficult to sleep: p=0.048, F=3.9; slept better-worse: p=0.001 F=10.8; woke often: p=0.048 F=3.9). Furthermore they reported reduced nocturnal restoration (rested-tired: p<0.001, F=31.6; at ease-tense: p=0.005, F=8.1; irritated-glad: p=0.011, F=6.5), reduced pleasantness and social orientation in the morning (pleasantness: p=0.001, F=10.6; social orientation: p<0.001, F=13.1). However, there were no significant interaction effects between exposure and noise sensitivity, suggesting that exposure had a similar effect on both groups.

Noise sensitive persons also reported enhanced sleep disturbance by vibration (p<0.001, F=17.2, Figure 2 left pane and noise (p<0.001, F=15.8, Figure 2 right pane) and here there was a significant interaction, showing that the noise disturbance difference between exposure and control was higher in noise sensitive persons (interaction p=0.038, F=4.3). The same interaction has been found in tendency for vibration disturbance (p=0.061, F=3.5).

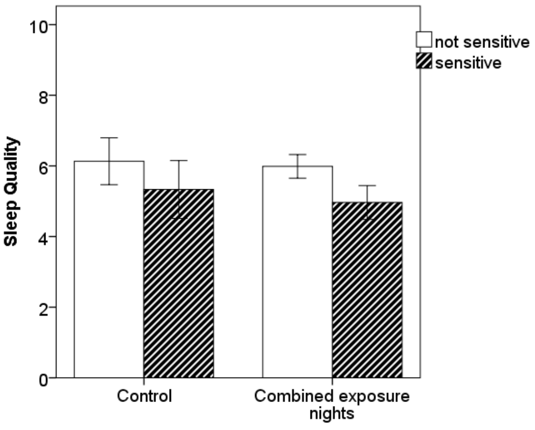

Figure 1 - Comparison of sensitive and non-sensitive persons: Mean rating of sleep quality during control and combined exposure nights, recorded immediately after awakening. Error bars show 95% confidence interval.

Table 3 - Comparison of sensitive and non-sensitive persons: Overview of the morning questionnaire results for the control and the combined exposure conditions. Variables names in bold indicate significant main effects between the sensitive and non-sensitive groups.

		Noise sensitivity							
		Non sensitive (N=38)				Sensitive (N=21)			
		Control		Exposure nights		Control		Exposure nights	
	Variable	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sleep quality	**Sleep quality** (0 = very bad, 10 = very good)	6.1	2.0	6.0	2.1	5.3	1.8	5.0	2.2
Disturbance	**Disturbance from vibration** (0 = not at all, 10 = extremely)	0.4	1.2	3.1	2.5	0.7	1.6	4.8	3.0
	Vibrations causing poor sleep (1 = not at all, 5 = extremely)	1.1	0.4	1.8	0.8	1.2	0.5	2.3	1.0
	Disturbance from noise (0 = not at all, 10 = extremely)	0.5	1.5	3.5	2.6	0.7	1.8	5.3	2.8
Sleep parameters	**Time to fall asleep** (mins)	25.5	17.1	27.9	16.2	31.3	21.4	36.3	24.4
	Estimated no. of wake-ups (n)	2.5	1.8	2.8	1.8	4.1	3.6	4.2	2.7
	Difficulties to continue sleeping (1 = did not wake, 2 = no difficulty, 3 = difficulty)	2.1	0.5	2.2	0.5	2.2	0.4	2.3	0.5
	Easy to sleep (0) **- difficult to sleep** (10)	4.2	2.6	4.3	2.5	4.6	2.8	5.2	2.6
	Slept better (0) – **worse** (10)	5.9	1.9	5.6	2.0	6.5	1.9	6.6	2.0
	Deep (0) – light (10) sleep	4.2	1.8	4.3	1.9	5.1	2.1	4.9	2.1
	Woke never (0) **- often** (10)	4.9	2.5	5.3	2.1	6.3	2.1	6.0	2.3
Nocturnal restoration	**Rested** (0) – **tired** (10)	4.2	2.1	4.1	2.1	4.8	1.9	6.2	2.3
	At ease (0) – **tense** (10)	3.4	1.7	3.6	1.7	3.3	1.5	4.5	1.9
	Glad (0) **- irritated** (10)	3.2	1.6	3.6	2.2	3.8	2.1	4.4	1.9
Mood	**Pleasantness** (1 = minimum, 4 = maximum)	3.2	0.4	3.2	0.5	3.0	0.4	2.9	0.5
	Social orientation (1 = minimum, 4 = maximum)	3.2	0.4	3.2	0.5	3.1	0.4	2.9	0.5
Stress-Energy	Stress	1.5	0.8	1.6	0.8	1.9	0.9	1.9	0.9
	Energy	2.2	0.7	2.2	0.8	2.3	0.9	2.1	0.8

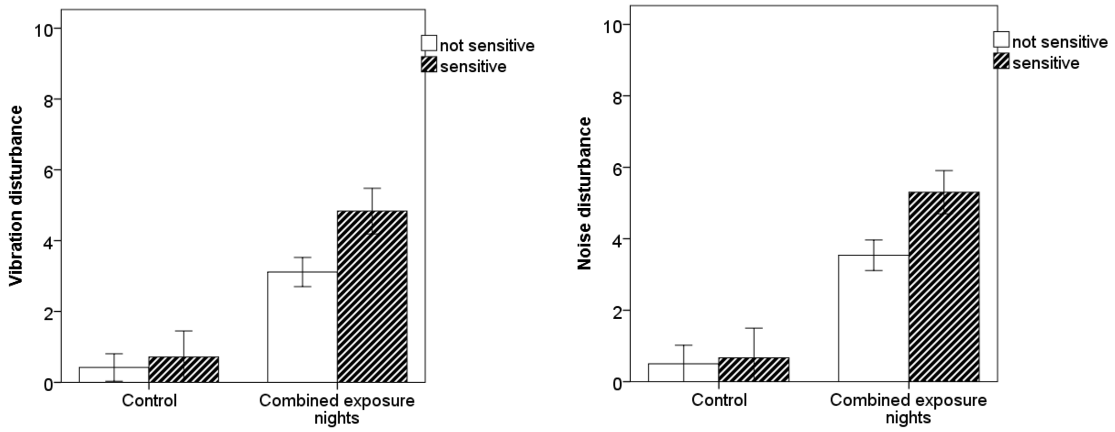

Figure 2 - Comparison of sensitive and non-sensitive persons: Mean rating of disturbance from vibration (left) and noise (right) during control and combined exposure nights, recorded immediately after awakening. Error bars show 95% confidence interval.

3.2 Polysomographical data

Due to a technical fault, PSG data was missing for a single person in the NVh20 condition (noise-sensitive female). As with the questionnaire results, objective data was pooled for all exposure conditions (Table 4).

Table 4 – Physiological sleep data for the noise sensitive and non-sensitive groups. WASO=Wakefulness After Sleep Onset, SSC=Sleep Stage Change, SWS=Slow Wave Sleep (deep sleep), REM=Rapid Eye Movement. Variable names in bold indicate significant main effects between the sensitive and non-sensitive groups.

Variable	Noise sensitivity							
	Non-sensitive (N=14)				Sensitive (N=10)			
	Control		Exposure nights		Control		Exposure nights	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sleep onset latency (mins)	28.9	18.1	19.3	15.2	22.9	22.1	15.7	14.4
Sleep efficiency (%)	89.7	4.6	90.8	4.7	90.7	6.4	91.8	7.9
WASO (mins)	20.6	12.7	24.3	18.0	21.6	16.5	23.7	31.4
Total SSCs (n)	35.4	6.6	36.9	6.8	29.9	5.6	37.8	10.4
Arousals (n)	53.9	15.9	55.9	16.6	43.1	12.2	49.9	19.1
Awakenings (n)	22.4	10.2	23.1	10.2	20.3	7.8	20.8	6.3
N1 (mins)	44.9	15.3	45.9	15.9	39.4	15.1	42.8	11.5
N2 (mins)	202.3	28.9	210.1	31.5	225.6	32.7	222.7	34.1
SWS (mins)	97.6	19.0	95.5	20.9	79.4	29.4	83.0	24.3
REM (mins)	85.7	19.2	84.2	20.5	91.3	18.5	92.0	21.2

There was a significant effect of noise sensitivity for time spent in SWS, with noise sensitive persons exhibiting less deep sleep compared to the non-sensitive group (F=4.3, p=0.05). As evident in Figure 3, sensitive person's deep sleep was particularly affected by the number of trains. Using a linear mixed model with compound symmetry, there was an effect for sensitive persons having a reduced amount of SWS in nights with 36 compared to nights with 20 trains (p=0.033). There was no effect of vibration amplitude (p=0.84). In the sensitive group there was also a tendency for time spent in N1 to increase linearly as a function of 8-hour acceleration (F=3.6, p=0.07).

Furthermore there was a significant correlation between SWS and disturbance from vibration (r=-0.504, p=0.012) and between SWS and disturbance by noise (r=-0.575, p=0.005) in the high vibration amplitude night (NVh36).

No significant differences were found between sensitivity groups for sleep onset latency (p=0.43), total number of sleep stage changes (p=0.78), total number of EEG awakenings or arousals (p=0.49 and 0.38 respectively), wakefulness after sleep onset (p=0.99), sleep efficiency (p=0.68) and total time in REM (p=0.37), N1 (p=0.56) or N2 (p=0.196).

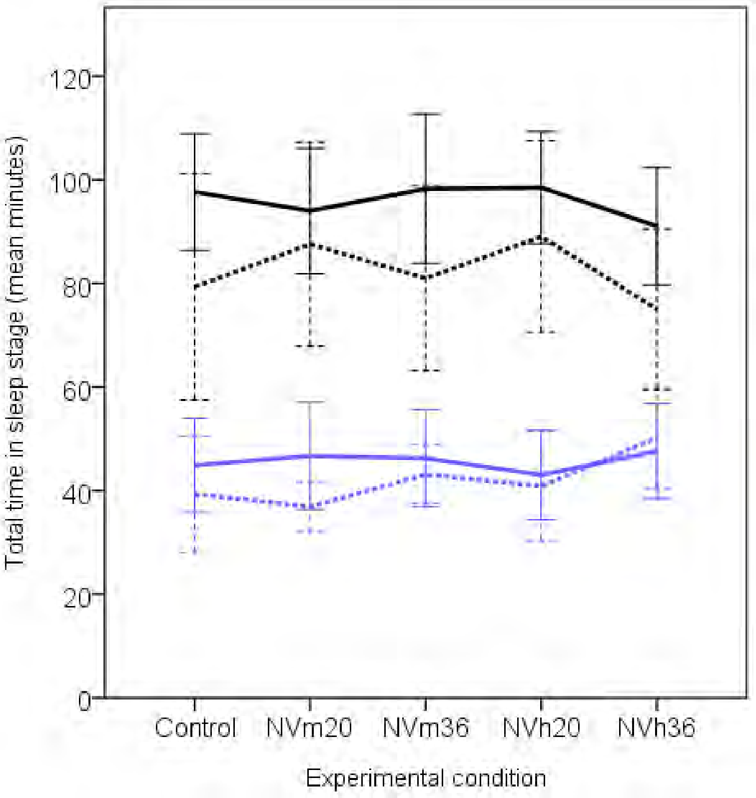

Figure 3 - Duration spent in SWS (black) and –N1 (blue) in each experimental night for the non-sensitive (solid line) and sensitive (dashed line) groups. Error bars indicated 95% confidence intervals.

4. DISCUSSION

There were no significant differences in EEG awakenings, SOL, sleep efficiency or WASO between the sensitivity groups, meaning that both spent around the same amount of time in sleep each night. However, the higher disturbance reported by the noise sensitive group during exposure nights taken with the similarity of the groups in the control suggests that stimuli occurring during periods of wakefulness were more negatively perceived. This is in line with annoyance studies whereby sensitive persons report higher annoyance for a given noise exposure [2].

The time spent in light sleep and deep sleep was rather stable for the non-sensitive group, whereas the number of events had an impact on the amount of SWS for the sensitive group. Since vibration amplitude had no effect, it is possible that this reduction is due to the noise component of the exposure, although this cannot be confirmed with the current study design. Other than this objective parameter, there were no differences between groups, suggesting that noise sensitivity is not an important modifier of physiological measures of sleep, supporting previous conclusions drawn by Marks and Griefahn [19].

Noise sensitivity was related to an overall reduction in subjective sleep parameters, independent of either the degree of exposure (vibration amplitude, number of events) or whether there was an exposure at all (control night vs. pooled exposure nights). The implication is that both the sensitive and non-sensitive groups were equally affected by nocturnal exposure to vibration and noise. Previous work has found that noise-sensitive individuals report reduced sleep quality following nights with traffic noise exposure compared to non-sensitive persons [20], an effect not observed in our studies. However, volunteers were only accepted into our trials providing they did not suffer from self-reported sleep problems as assessed during the screening process via binary yes/no response questions including “I often have trouble falling asleep”, “I wake frequently at night”, “I rarely get enough sleep”, “I often sleep for a while during the day” and “I am very tired in the morning”. This could mean that the sensitive sample only represented a somewhat resilient subgroup of the wider noise sensitive population, which would go some way towards explaining the similarity that exposure had on both sensitivity groups in terms of subjective parameters including sleep quality.

The sample size limits the conclusions that can be drawn, particularly with respect to the PSG data. In Study II from which physiological reactions have been analysed, only 10 of the 24 participants were classified as noise-sensitive. Analysis of PSG data from Study III along with potential further sleep studies conducted by the research group will aim to expand upon the existing results.

In conclusion, noise-sensitive persons report overall reduced sleep quality, confirmed by reduced SWS and higher disturbance from nocturnal traffic exposure. The overall reduced time spent in SWS may make noise sensitive individuals particularly vulnerable to nocturnal traffic exposure.

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