The impact of railway freight with regard to vibration level, noise and number of trains on sleep

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ABSTRACT

As part of the European CargoVibes project, the impact of vibration and noise from rail freight traffic on sleep was investigated experimentally. In three studies, 59 test persons aged 19-30 years (mean 23.1) were exposed to various conditions: train passages with: noise only (N) (49.8 dBA_{Fmax}), vibration only (V) and noise and vibrations (NV) with maximum weighted (W_d) vibration levels of: 0.0058m/s^2, (Low), 0.0102 m/s^2 (Moderate) and 0.0204m/s^2 (High) and 20, 36 or 52 passages during a night. Sensitivity to noise and gender was balanced within the design. Subjective ratings were collected in the morning and evening using questionnaires. Physiological reactions of sleep were recorded using polysomnography and are reported elsewhere. Results show that participants were able to well differentiate between noise and vibration induced sleep disturbance. Sleep quality and in tendency also nocturnal restoration were negatively affected by vibration level when keeping the number of trains the same. Increasing the number of trains resulted in a tendency of reduced sleep quality. Vibration only was found to cause sleep disturbance. The data provide a first basis for dose response relationships.
Environmental vibration is concluded to be of importance for sleep at levels encountered in the field for people living in the vicinity of freight railway lines and as such should be considered when assessing the health consequences of freight trains.
Keywords: Vibration, Sleep disturbance, dose response

INTRODUCTION

As pointed out in the White paper for European transport the rail transportation is aiming to increase its market share of goods transportation from 8 % in 2001 to 15 % in 2020 (EC 2001). To facilitate this within the existing railway schedules, most of this transportation will be done during night time slots. Noise and vibration will potentially increase, with annoyance and sleep disturbance as critical hindrance for this development. While quite many studies have evaluated the impact of noise from railway on annoyance and sleep e.g. (Knall and Schuemer 1983, Aasvang et al. 2008, Pennig et al. 2012); and more specifically for sleep disturbance (Basner et al. 2011, Elmenhorst et al. 2012) (Griefahn et al. 2006, Saremi et al. 2008, Hong et al. 2010, Aasvang et al. 2011) (Lercher et al. 2010)very little guidance can be given to human response due to vibration from rail transportation. To our knowledge only three previous projects have evaluated the impact on sleep with reference to rail vibration (Ohrstrom 1997, Klaeboe et al. 2003, Öhrström E 2009) Öhrström and colleagues report on considerably higher sleep disturbance in areas with both high noise level and

vibration and the data was also supported by experimental studies where sleep disturbance was higher for 1,4 mm/s (Nordic comfort weighted) as compared to 0,4 mm/s (Öhrström E 2009). Due to the study design, it was not possible to draw conclusions about dose response relationships for various levels of vibrations. On the other hand (Klaeboe et al. 2003) derived dose response relationships of annoyance and activity disturbance and vibration levels based on survey data from people being exposed to vibrations from a variety of transportations including rail. Although no significant difference in annoyance response was found between sources, it is cannot be assumed that sleep disturbance will be affected similarly by various sources also taking noise into account. For example freight trains have been found to cause more frequent awakenings (Saremi et al. 2008) stronger autonomic response (Tassi et al. 2010) and greater nocturnal annoyance (Pennig et al. 2012) than passenger trains.

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 Persson Waye et al 2014). During the course of three years, a total of three laboratory studies involving 59 participants over 350 person-nights have been obtained. This dataset provides us a unique opportunity to evaluate the impact of freight train vibration exposure on sleep and to provide a first basis for a dose response relationship.

METHODS

The methods have been described in detail in (Smith et al. 2013) and will therefore be described here in less detail.

Participants

For the studies, female and male volunteers aged 18 – 30 were recruited. Exclusion criteria were i. reduced hearing acuity (>20 dB hearing loss at a single frequency as determined via audiometric testing, Entomed SA 201), ii. BMI <18.5 or ≥25, iii. self-reported snoring or sleep problems, iv. self-reported allergies and/or hypersensitivity and v. being a tobacco user or caffeine dependent. Noise sensitivity was assessed with a direct question and answered on a five grade scale (not sensitive to extremely sensitive) and used as a proxy also for vibration sensitivity. The volunteers were financially reimbursed for their participation and the studies were approved by the Ethics Committee of Gothenburg.

Evaluation of sleep

Questionnaires adapted from (Öhrström E 2009, Persson Waye et al. 2013) were administered each morning immediately following awakening. Questions included 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 usual and whether it was deep/shallow. At the end were questions on mood (Sjoberg et al. 1979) and stress/energy (Kjellberg et al. 2000). A shorter form of the questionnaire was

distributed in the evening, but results will not be presented here.
Polysomnography (PSG) recordings included electroencephalogram (EEG), electrooculogram (EOG) and submental electromyogram (EMG), breathing, pulse and oxygen saturation. These are reported in detail elsewhere (Smith et al. 2014).

Laboratory facilities and exposures

The sleep laboratory is constructed as an apartment with a separate entrance to which the subjects have their own key (amm.se/soundenvironment). 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 loudspeakers in the ceiling 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.

Figure 1 Left pane: Bedroom. Right pane: Electrodynamic transducer within enclosure (base removed for photograph)

Eight different exposure scenarios were created over the three studies. Based on field measurements, the vibration signal was an amplitude modulated 10 Hz sinusoid, which was input along the length of the bed (Smith et al. 2012). 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 (1s 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. 2013)). Experimental nights consisted of 20, 36 or 52 trains. The weighted night time 8-hour vibration data for all exposure conditions together with the maximum velocity used for the dose response relationships are presented in Table 1. All values are W_d weighted according to ISO 2631-1 (ISO 1997). Root mean square (rms) was calculated according to Equation 1.

Equation 1

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

Table 1 Weighted (W_d, ISO-2631) eight-hour rms vibration for all experimental nights and maximum velocity for the exposure conditions. Denotations: N=noise exposure, V=vibration exposure, l/m/h=low/moderate/high vibration amplitude, 20/36/52=number of events.

Experimental exposure	$rms_{d,23\text{-}07}$ (ms^{-2})	W_d weighted max velocity (mm^{-1})
N36	-	
NVl36	0.0007	0.093
NVm20	0.0010	0.164
NVm36	0.0014	
NVh20	0.0019	0.325
Vh36	0.0027	
NVh36	0.0027	
NVh52	0.0033	

Study design and statistical analysis

Each trial consisted of one habituation night and one control night before four experimental nights. The exposure order was randomized across participants using a Latin square design. Care was exercised to spread gender and noise sensitivity approximately equally within the exposure nights.

The participants were instructed to arrive at the sleep laboratory by 20:00 in the evening, go to bed and begin attempting to fall asleep at 23:00 and were woken at 07:00 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.

Table 2 Study designs.

Study	Vibration amplitudes	Number of trains	Number of participants	Measures
1	Low, moderate, high, noise only	36	12	Questionnaires, heart rate
2	Moderate, high	20, 36	24	Questionnaires, PSG, heart rate
3	High (with & without noise), noise only	36, 52	23	Questionnaires, PSG, heart rate
Total	Low, moderate, high (with & without noise), noise only	20, 36, 52	59	

Subjective data were combined from all three studies and analyzed in SPSS v.18 (SPSS Inc., Il., USA) with a univariate ANOVA model, including the individual participants as random effects to correct for dependent data. Three main research questions were tested and the F-contrasts were built accordingly. Post-hoc tests were performed uncorrected since that given the number of variables, the resulting

corrections would be too conservative and lead to an underestimation of potential effects. The three hypotheses are as follows:

A) Is sleep disturbance related to vibration amplitude given a constant number of trains?
B) What is the influence of number of trains?
C) Is sleep disturbance related to vibration or to noise or to the combined exposure?

The derivation of dose-response relationships for sleep disturbance was performed according to the same classification criteria used for annoyance described by (Miedema and Oudshoorn 2001). The assumption is that the 11-point sleep disturbance scale divides into equally spaced intervals. The category boundaries are determined by Equation 2 and subsequent rescaled sleep disturbance values given in table 3.

$$scores_{boundary,i} = 100 \, {}^{i}\!/_{m}$$

Equation 2

A logistic regression model using the base 10 logarithm of the vibration exposures was used to generate dose-response curves for the probability of persons reporting these different levels of sleep disturbance by vibration as a function of 8 hour rms acceleration and Wd weighted max velocity (Table 2). Nights without experimental vibration (control and noise-only conditions) were assumed to have an rms of 0.0001 ms^{-2} and velocity of 0.005 mm^{-1}.

Table 3 Boundaries and midpoints for sleep disturbance scale.

Effective categories *m*	Boundary quantifications *b*	Rescaled sleep disturbance rating
11	0-9-18-27-36-45-55-64-73-82-91-100	4.5-14-23-32-41-50-59-68-77-86-95

RESULTS

To examine the significance of *vibration amplitude*, exposure conditions where the number of trains was the same were analyzed. In relation to the vibration amplitude, we found significant negative effects on sleep quality, (F=3, p=0.021), (Figure 2 left pane) and sleep disturbance from vibration (F= 40; p<0.001; right pane black bars) and noise (F=46; p<0.001, right pane, grey bars). Post-hoc comparison revealed that sleep quality was significantly lower in the NVh36 compared to: the control night (p=0.026), the noise only exposure (p=0.031) and the low vibration exposure (p=0.048). The right pane in Figure 2 indicates that participants were well able to differentiate between noise and vibration induced sleep disturbance. Disturbance by vibration increased with increasing vibration amplitude, while noise disturbance was similar across all exposure conditions suggesting that vibration exposure did not affect noise disturbance.

No significant effect was found of *number of trains* in the high vibration conditions, whereby increasing the number of trains from 20 to 36 to 52 did not increase the perceived negative impact on sleep. When comparing exposure nights with high or moderate vibration with 20 or 36 trains per night we found a tendency for a main effect of train number for the overall sleep quality (F=3.4, p=0.08, (Figure 3).

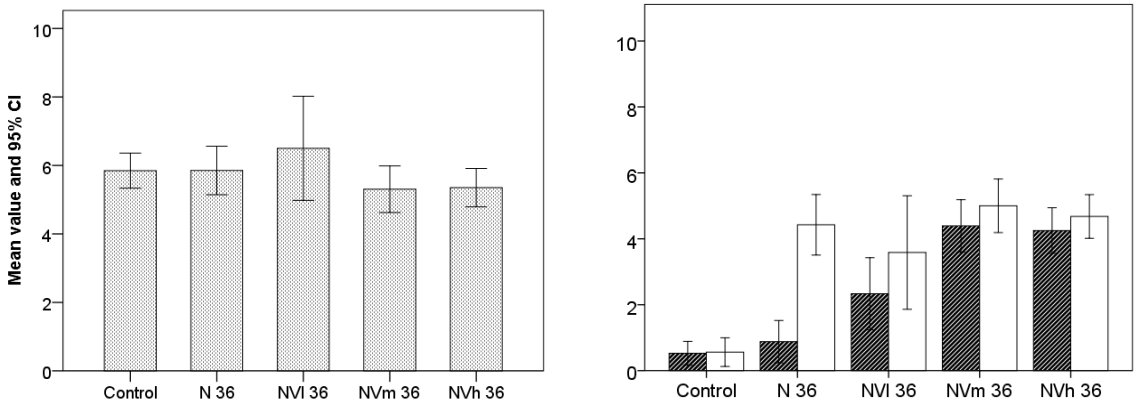

Figure 2. Left pane shows the mean ratings of sleep quality (0 very poor - 10 very good) and right pane the mean values of sleep disturbance (0 not at all - 10 extremely) due to vibration (black bars) and due to noise (white bars). Error bars show 95% confidence interval.

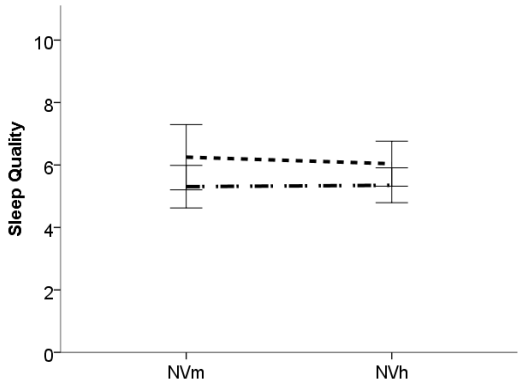

Figure 3. Mean rating of sleep quality (0 very poor – 10 very good) during exposure nights, divided into moderate versus high vibration and 20 trains (dotted line) and 36 trains (dashed line). Errors bars show 95% confidence intervals

The interactions between amplitude and number of trains were generally small and significant only for the disturbance from noise (F=8.8, p=0.007) and for vibrations causing poor sleep (F=4.3, p=0.05), both indicating an effect of amplitude in the low number of trains but not for the high number of trains.

To elucidate the *relative importance of vibration and noise*, conditions with 36 trains with vibration only, noise only and a combination of noise and vibration all at high amplitudes were compared. Self-reported disturbance from vibration alone and in combination with noise was found to be significantly higher compared with the control and noise only conditions (F=59; p<0.001). Noise disturbance was found to be significantly lower for control and vibration only (F=59; p<0.001) as compared to Noise only and Noise and Vibration only. This again pointing to the fact that subjects could well differentiate between vibration and noise, but not giving much guidance of the relative importance of the exposure combinations due to the phrasing of the questions.

Sleep disturbance was nonlinearly fitted to the vibration exposures (rms and VdMax) and the derived dose response models shown in Figure 4. The right pane provides an estimate of the importance of the maximum value with no reference to number of trains over a night, while the left pane takes the overall exposure over a night into account when calculating the dose.

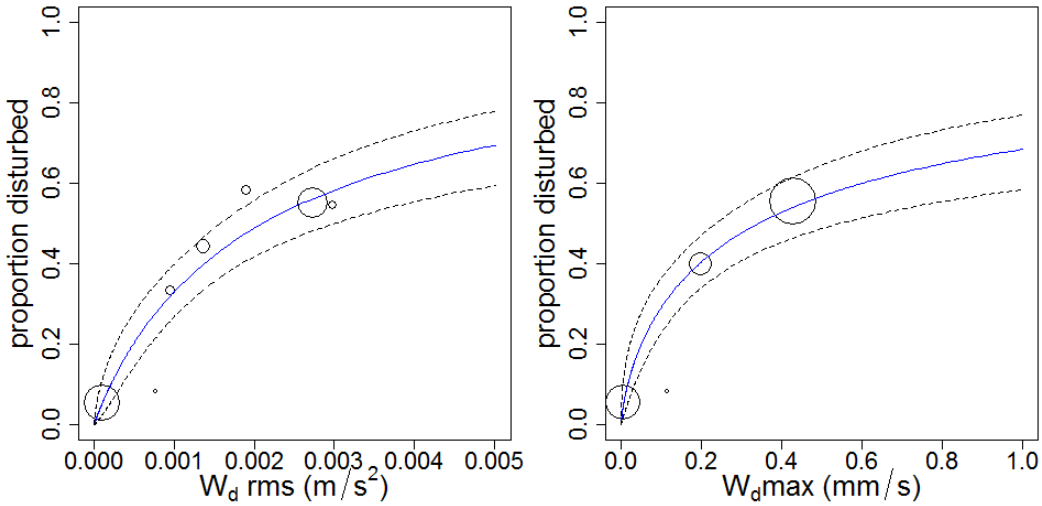

Figure 4. Proportion of subjects reporting being sleep disturbed (≥5 on 11-point scale) by vibration as a function of 8 hour rms vibration (left pane) and maximum weighted velocity (right pane). Dashed lines indicate point-wise 95% confidence intervals. The sample size and subsequent weighting of each point is indicated by the point area. Observe that derived data is limited to the exposures related to the circles.

Both curves indicate that sleep disturbance initially increases with a higher vibration amplitude. The left pane representing an exposure dose over the night indicates that disturbance is approximately independent of the number of trains in the high vibration conditions.

CONCLUSIONS

The studies show that freight train vibration and noise in combination and in isolation negatively impact perceived sleep. Disturbance increases with vibration amplitude, while the number of trains seems to be of importance for the moderate vibration level but not for the high vibration level. Vibration exposure alone was found to impact on sleep disturbance, hence reducing noise exposure in the field might not be sufficient to protect against disturbance in areas of high vibration such as residences in close proximity to freight lines.

These trials provide an extensive set of exposures that have been used to derive a first basis for a dose response relationship. In the next step there is a need to extend the knowledge of human response to exposures in the lower vibration region <0.2 Wd max (mm/s) and to validate the dose response data to field settings.

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