Freight trains, nocturnal vibration and noise, and their physiological effects during sleep

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ABSTRACT

There has been much previous research examining the effects of environmental noise on sleep, but the specific influence of vibration exposure has largely been neglected and primarily limited to cross-sectional field studies. Within the EU CargoVibes project, we experimentally investigated physiological reactions to freight train vibration and noise exposure during sleep. Polysomnography was used to determine the impact on sleep architecture, in terms of macrostructure and for event-related autonomic and cortical arousals. The work aimed to examine the effects on sleep of vibration amplitude, number of events, and the interaction of vibration and noise. Nights with 36 events and high vibration were found to result in greatest sleep fragmentation, more changes to lighter sleep stage, shorter continuous time in slow wave sleep and earlier awakenings than the control, and increased wakefulness and reduced rapid eye movement sleep relative to the 20 train night. The likelihood of the occurrence of event-related awakenings, arousals and changes in sleep depth all increased with vibration amplitude. Heart rate response was greater during exposure to high than moderate vibration. Comparison between first and second half of the night indicated that cardiac reactions sensitized to repeated vibration exposure.

Vibration in residential environments from railway freight contributes towards sleep fragmentation which may have implications for health outcomes. Guidelines to prevent adverse health outcomes for freight lines where there is a risk for vibration exposure therefore need to consider not only noise but also the added impact of vibration.

INTRODUCTION

Humans spend approximately one third of their lives asleep, a biological process necessary for physical and mental wellbeing (Muzet 2007), clearance of neuronal waste products (Xie et al. 2013) and memory consolidation (Stickgold 2005). Sleep disturbance by environmental noise exposure has been recognized as a serious non-auditory health issue (Basner et al. 2013) and nocturnal railway noise is associated with increased sleep medicine intake and motility reactions (Lercher et al. 2010) and reduced daytime attentional processes (Tassi et al. 2013). Freight train noise in particular have been found to cause more frequent awakenings (Saremi et al. 2008), stronger cardiac activations (Tassi et al. 2010) and greater nocturnal annoyance (Pennig et al. 2012) than passenger trains.

Previous work examining the influence of railway freight on sleep has overwhelmingly focused on noise exposure, without consideration of the vibration that can also be present. Due to the high axle loads of freight trains, high amplitude low frequency vibrations are often generated in the ground which may then propagate into nearby

residences. The only existing body of laboratory work examining the impact of vibration from rail transportation on sleep found that increasing vibration from 0.4 mm/s to 1.4 mm/s resulted in negative effects on sleep quality, alertness, restlessness, awakenings and difficulties falling asleep, all measured using questionnaires (Ögren et al. 2009, Öhrström et al. 2009).

Subjective measures such as questionnaires are a cost-effective method of measuring sleep, but they do not necessarily accurately reflect acute physiological responses to vibration and noise (Baker et al. 1999) which may be indicative of sleep disruption and fragmentation. As such the current project aimed to examine the impact of vibration and noise from freight trains on objective sleep parameters.

METHODS

Three laboratory studies were conducted between November 2011 and November 2012, all with the purpose of examining the effects of freight trains on sleep. Study 1 aimed to investigate the influence of vibration amplitude on sleep. Study 2 aimed to gain a deeper understanding of the effects of vibration amplitude and also to examine the influence of number of train passages during the night. Study 3 aimed to investigate the interactions of vibration and noise exposure, and additionally to study a further increase in number of trains.

Laboratory facilities

The research group's sound environment laboratory (www.amm.se/soundenvironment) was furnished to resemble a home environment. The laboratory includes a private entrance, living, cooking and cleaning facilities and private bedrooms for study participants.

Noise was reproduced using 88 10" loudspeakers within the bedroom ceilings and speakers in the upper corners of the rooms. Background ventilation noise was artificially introduced at 25 dBA during study periods. Vibration was applied horizontally lengthwise along the bed using electrodynamic shakers within enclosures mounted to the underside of the bed frame.

Photographs of the laboratory facilities are available elsewhere at the congress (Persson Waye et al. 2014).

Exposures

A detailed description of the exposures used has been reported previously (Smith et al. 2013) and they are therefore only summarized here.

Five freight trains were synthesized based on field measurements. Noise levels varied between $L_{AEq,pb}$ 44.0 – 45.6 dB, $L_{AF,max}$ 47.2 – 49.8 dB and durations were 11.5 – 59.6s.

Vibration was an amplitude modulated 10 Hz sinusoid. This was adjusted to give four vibration amplitudes, 'High', 'Moderate', 'Low' and 'None' (i.e. noise only). These are weighted using the W_d filter as the exposure is horizontal for recumbent persons (ISO 1997). Subsequent exposures are reported as accelerations and velocities in Table 1.

Table 1 Vibration amplitudes. All values are W_d weighted.

Vibration exposure	Maximum acceleration (m/s^2)	Maximum velocity (mm/s)
High	0.0204	0.325
Moderate	0.0102	0.164
Low	0.0058	0.093
None	-	-

Experimental protocol

Three separate trials were conducted, involving a combination of different vibration and noise scenarios. A summary of the designs of the studies is presented in Table 2. Study 1 had 36 trains per night, with differing vibration amplitudes between nights. Study 2 used a matrix of two vibration amplitudes and either 20 or 36 trains. Study 3 had three nights with 36 trains, either noise only, vibration only, or noise and vibration together. The fourth night had 52 trains with both noise and vibration. In all studies the order of exposure conditions was distributed equally over trial weeks with a Latin square design.

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	

Over the three trials, 59 healthy volunteers aged 19-30 (mean 23.1, SD ±2.8 years, 31 women) with no self-reported sleep problems were recruited. All had good hearing as determined by pure tone audiometry (≤20 dB HL), provided informed written consent and were permitted to discontinue at any time.

Each volunteer spent a total of six consecutive nights in the laboratory. The first night served as adaptation to the environment and polysomnogram equipment. The second night was used to measure baseline sleep in the absence of train exposure. Freight exposures were introduced during nights 3 – 6.

Sleep was measured each night using ambulatory polysomnography (PSG) instruments (Figure 1). This involved using surface electrodes (≤5kΩ) to record electrical brain wave activity (EEG), eye movements (EOG) and chin muscle movements (EMG). Cardiac activity was recorded using ECG. Finger pulse amplitude and blood oxygen were measured with a finger oximeter. Respiratory movements were measured with thorax and abdomen effort belts. All measurements were performed according to AASM standards (Iber et al. 2007).

Figure 1 Polysomnogram setup

Subjects were instructed to start trying to fall asleep at 23:00 each night, and were woken with an alarm call at 07:00 each morning. Within 15 minutes of the alarm they completed questionnaires to measure their subjective sleep quality, disturbance, tiredness, mood, impressions of sleep etc. Further details of these measures are available elsewhere at the congress (Persson Waye et al. 2014).

Throughout the course of the study, participants were prohibited from alcohol at all times and caffeine after 15:00. They arrived at the laboratory by 20:00 each evening for relaxation before sleep and to allow time to connect the polysomnogram apparatus. They refrained from napping or from sleeping outside of the allotted sleep times.

Analysis

The average heart rate response in different exposure conditions was determined over the 60s following the start of the train. Events where the subject was awake at train onset or awoke during the pass-by were excluded from analysis. The approach used is described in detail elsewhere (Croy et al. 2013).

Sleep stage was determined by manual inspection of the PSG data in 30s epochs by a qualified sleep technologist. EEG arousals (3-15s) and awakenings (>15s) were scored using ASDA criteria (Bonnet et al. 1992). Rapid eye movement (REM) sleep was considered to be the ‘lightest’ sleep stage (Carter et al. 2002).

A Matlab algorithm was developed to determine the probability that any given train within an exposure night would result in an arousal or awakening. A 60s screening window from the start of each train was used to define whether such a response was event-related. A similar algorithm was used to determine the likelihood of a train resulting in a sleep stage change (SSC) to a ‘lighter’ depth. The sleep stage at train onset was used as the baseline and compared to the subsequent three epochs.

Mixed models were used for analysis of the sleep data in order to account for repeated measurements. Continuous data were analyzed assuming normality (after a

suitable transformation if required) in a linear mixed model. Count data and event-related probabilities were analyzed within a generalized linear mixed model framework, assuming Poisson distribution and binary distribution, respectively. Tukey corrections were used to account for multiple hypothesis testing.

RESULTS

Macrostructure

A selection of sleep macrostructure parameters based on variables thought to be important indicators of sleep disturbance are presented in Table 3 (Griefahn et al. 2008).

Sleep onset latency (SOL), maximum continuous time in slow wave sleep and time to first awakening were all significantly shorter in nights with high vibration and 36 trains (NVh36) relative to the control (Con) in study 2. Increasing the number of trains from 20 to 36 in high vibration nights resulted in increased wakefulness after sleep onset (WASO) and time in sleep stage 2 (N2) and a decrease in time spent in REM. The total number to sleep stage changes (SSCs) was higher in nights with 36 trains (both moderate and high vibration) than in the control in study 2. In study 3, REM latency (RL) was higher in the vibration only night (Vh36) than in the condition with noise, vibration and 52 trains (NVh52).

No effects of exposure were found for slow wave sleep latency (SWSL), time in stage 1 sleep (N1) or time in slow wave sleep (SWS) in either study.

Table 3 Sleep macrostructure. Values in bold indicate statistically significant comparisons ($p<0.05$). All values in minutes unless otherwise specified.

	Study 2					Study 3				
	Con	NVm20	NVh20	NVm36	NVh36	Con	N36	Vh36	NVh36	NVh52
SOL	**26.4**	16.6	22.3	17.4	**15.3**	20.5	28.6	21.1	23.3	19.0
SWSL	20.0	18.2	20.5	19.4	23.1	18.2	19.8	22.5	18.7	18.9
RL	80.7	81.0	87.9	84.9	96.0	82.8	81.9	**96.3**	80.8	**67.4**
WASO	21.0	28.3	**19.2**	22.3	**26.4**	19.9	15.8	25.5	16.6	24.5
N1	42.6	42.6	42.2	45.0	48.7	39.3	41.8	40.9	41.0	41.1
N2	212.0	211.2	**210.9**	215.0	**224.0**	217.7	204.5	206.8	208.0	203.3
SWS	90.0	91.3	94.8	91.1	84.4	89.6	96.7	95.5	94.4	90.8
REM	88.0	90.0	**90.7**	87.6	**81.4**	93.5	93.2	90.4	97.0	101.7
Max. continuous SWS	**32.0**	31.2	28.8	32.3	**26.4**	32.5	31.9	32.6	32.5	31.3
First awakening	**39.8**	16.7	27.2	28.8	**14.5**	36.8	27.6	19.1	22.0	23.9
SSCs (n)	**33.1**	36.2	37.0	**37.7**	**38.3**	32.9	34.5	32.5	35.5	36.2

Nights with 36 trains and high vibration resulted in the greatest sleep fragmentation, reflected by changes to lighter sleep stage (n=38.3), shorter continuous time in slow wave sleep (34.4 min), early awakenings (14.5 min), increased wakefulness (26.4 min) and reduced REM sleep (81.4 min), although these effects were only observed in study 2. In study 2 no effects on macrostructure were observed in moderate vibration nights despite the noise levels being the same as in high vibration.

Therefore the effects observed are likely attributable to the higher vibration amplitudes.

Cortical reactions

Relative to the chance of reactions occurring spontaneously as determined in the control nights, the probability of EEG reactions (arousals and awakenings, $p<0.001$) and SSCs ($p<0.0001$) was higher during all exposure nights. Probabilities were higher in high vibration nights than moderate vibration nights for EEG reactions ($p<0.001$) and SSCs ($p<0.05$), irrespective of number of trains. The number of train passages was not found to affect reaction probability, and so reaction likelihoods from all nights with the same vibration amplitude (high or moderate) were combined. The results are shown in Figure 2, which indicates how event-related reaction probabilities increase with vibration amplitude.

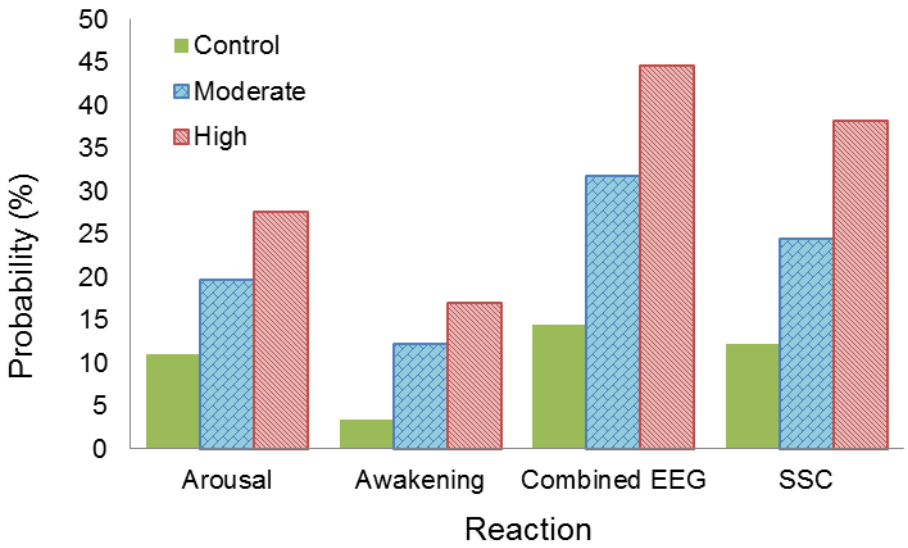

Figure 2 Reaction probabilities for arousals, awakenings, combined EEG response and sleep stage changes in the control, moderate and high vibration conditions

Heart rate

A significant main effect of vibration amplitude was found for heart rate, with a higher increase for high vibration trains compared with moderate vibration (Area under curve analysis, $p=0.01$). No effect of number of trains was observed and so all nights with the same vibration amplitude (moderate or high) were combined. The averaged heart rate response to events is shown in Figure 3. For both moderate and high vibration there was an initial increase above baseline ($p<0.05$) followed by a further delayed response above baseline (21-22s after trains start for moderate vibration, 20-48s for high vibration, $p<0.05$). The delayed increase in heart rate was greater for high vibration trains ($p=0.0006$). There was a tendency for a higher delayed response in males ($p=0.055$).

During study 3 there was a main effect for the magnitude of event-related heart rate increase being greater in the second half of nights (03:00-07:00) relative to the first four hour period ($p=0.015$). For individual exposure conditions this difference was significant only for experimental nights with vibration in the absence of noise ($p<0.05$). The implication is that autonomic reactions may sensitize to vibration as the night progresses.

Repeated cardiac activations may in the long term be a risk factor for the genesis of cardiovascular disease. In the field this could potentially be exacerbated by stronger heart rate responses due to the added exposure of vibration, although long term studies are lacking.

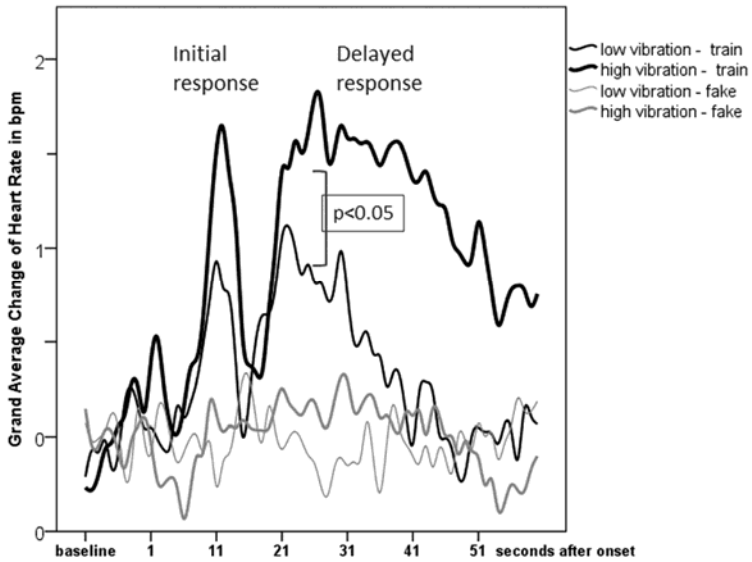

Figure 3 Averaged heart rate response in the 60s following the start of a train. Adapted from Croy et al. 2013

Interactions of exposures

The additional probabilities of event-related arousals and SSCs within study 3 exposure nights relative to spontaneous reactions are displayed in Figure 4. Also shown is the sum of probabilities from the noise only and vibration only conditions. For SSCs the summation of noise only and vibration only agrees to within 0.5% of the combined exposure night. For arousals the deviation is 0.4%. Therefore for these reactions, vibration and noise appear to be directly additive in terms of response likelihood. Both exposures are therefore of importance when considering the impact of freight on sleep.

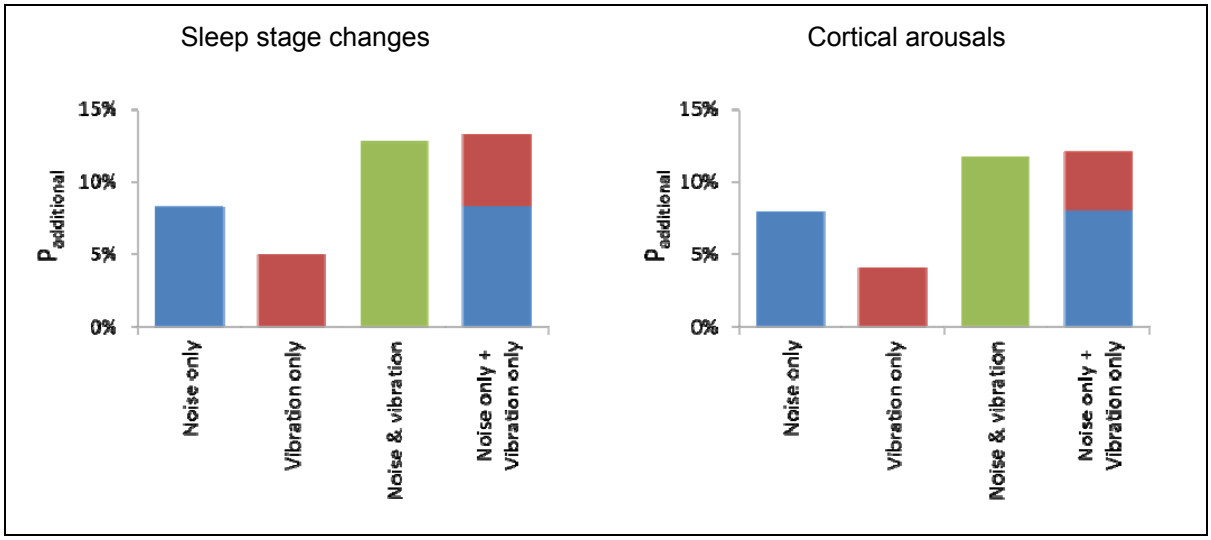

Figure 4 Interactions of noise and vibration

CONCLUSIONS

Vibration exposure from railway freight was found to contribute to disruption of sleep in terms of overall physiological effects during the night, the likelihood of event related reactions and increased autonomic response. The impact was strongest for the highest vibration amplitudes investigated. Such exposure in residential environments may therefore contribute towards sleep fragmentation which has potential implications for health outcomes. Guidelines for freight lines where there is a risk for vibration exposure therefore need to consider both vibration and noise.

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