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4aNSa9. Nocturnal vibration and noise from freight trains impacts sleep  
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There is a proposed increase in the number of freight trains on the European railway networks, with this growth being facilitated through using the available night time periods. 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 the sleep of residents. To investigate the potential impact we conducted a laboratory trial on 24 young healthy persons 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 moderate (0.0102 m/s\(^2\)) and high (0.0204 m/s\(^2\)) maximum *W*\(^d\) weighted vibration amplitudes and low (20) and high (36) number of train passages were simulated with noise levels being of the same order between nights. Polysomnography was used to record sleep stage and EEG arousals and awakenings. Event-related cardiac activations were analysed using ECG recordings. Questionnaires were administered to obtain subjective sleep parameters. Sleep was more fragmented during nights with higher vibration amplitudes and number of events. Furthermore, heart rate response was higher in the high vibration condition. Results from the subjective data showed less discrimination between nights.

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INTRODUCTION

There has been a great deal of previous research investigating the effects of nocturnal rail traffic noise exposure on sleep, both in field and laboratory environments [1,2,3,4]. However, the influence of vibration is an area in which little work has been performed. Field work investigating rail traffic has found that higher sleep disturbance was reported in areas with strong vibrations compared to areas with similar noise levels but lower vibration amplitudes [5].

The amount of goods traffic on the European rail networks is projected to increase, and this proposed growth is to be made possible by freight operators utilising the night-time periods [6]. The most serious health impact is therefore envisaged to be sleep disruption arising from vibration and noise. The E.U. project CargoVibes aims to evaluate this potential impact on persons living nearby to freight railway lines [7]. To contextualise the problem, recent field studies have reported between 3 and 19 nocturnal freight passages in areas of Norway [1] and up to 150 in Germany [8].

Previous work examining the effect of vibration from trains on sleep has been performed as part of the Swedish TVANE project [5,9]. These laboratory studies found that subjective sleep disturbance was higher in nights with maximum vibration amplitudes of 1.4 mm/s compared to nights with 0.4 mm/s (weighted according to the Nordic standard SS 460 48 61 [10]). Sleep quality was correspondingly lower in the nights with higher vibration. However, these trials did not focus solely on freight and used only subjective methods in the form of questionnaires to evaluate the effects. Additional work involving physiological measurements and the use of improved vibration generation equipment will allow a more detailed investigation into the human response to vibration during sleep. This paper presents a laboratory study performed with high ecological validity examining the impact of nocturnal vibration exposure from freight trains on human sleep.

METHODS AND MATERIALS

Study subjects were required to be aged 18 – 30, maintain normal sleeping patterns, not use tobacco products and have good hearing (≤20 dB HL, 250 Hz – 8 kHz). To avoid potential breathing difficulties or apnoea they were required to have a BMI within the normal range of 18.5 - 24.99 [11]. To allow for investigating differences in response between self-reported noise sensitive and non-noise sensitive persons an equal number of females and males in each of these categories were strived for. Subjects rated their noise sensitivity on a 5-point semantic scale with possible responses of “Not at all sensitive”, “Not particularly sensitive”, “Somewhat sensitive”, “Very sensitive” and “Extremely sensitive”. Persons rating themselves as not at all or not particularly sensitive were categorised as being non-noise sensitive. Respondents giving answers as being, somewhat, very or extremely sensitive were categorised as noise sensitive.

Twenty-four young healthy subjects were recruited for the study (13 females 11 males, age range 19-28, mean 22.9 s.d. 2.8 years). Ten were classified as noise sensitive (7 females, 3 males). Twenty three were students and one was in employment. The study was approved by the University of Gothenburg ethics committee, and all subjects provided informed written consent and were financially compensated for participation.

Exposure

Noise exposure consisted of five individual freight train recordings of between 11.5 – 56.9 s in duration, filtered to correspond to a closed window. Rise time was between 7.9 – 9.8 s. More detailed information is available elsewhere [12].

Vibration was generated by an electrodynamic transducer mounted to the underside of the bedframe. Based upon previous work it was applied in the horizontal direction (head-foot) in the form of an amplitude modulated 10 Hz sinusoid [13]. Two maximum accelerations were used as per Table 1.
Table 1. Vibration data for exposures used in the sleep trial. Values are horizontal vibration measured on the frame of an unloaded bed.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Unweighted rms acceleration (m/s²)</th>
<th>Wₜ Weighted max. acceleration (m/s²)</th>
<th>Unweighted max. velocity (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (high)</td>
<td>0.072</td>
<td>0.0204</td>
<td>1.61</td>
</tr>
<tr>
<td>M (moderate)</td>
<td>0.036</td>
<td>0.0102</td>
<td>0.81</td>
</tr>
</tbody>
</table>

Two separate distributions of train events were arranged. The number of passages per night was based upon data from existing field studies [1,8]. The high intensity exposure nights consisted of 36 events, and the lower intensity nights had 20 trains. In both cases there were more trains in the hours between 23-01 and 05-07 to reflect typical timetabling scenarios. In the 20 event night, Lₐₑₙₗₕₐₜₙₖₛ₉₅₆₈₃₈₇ = 29.3 dB with a range of Lₐₑₙₗₕₐₜₙₖ₄₉₅₆₈₃₈₇ = 27.6 to 30.1 dB between individual hours. In the 36 event night, Lₐₑₙₗₕₐₜₙₖ₄₉₅₆₈₃₈₇ = 31.3 dB with a range of Lₐₑₙₗₕₐₜₙₖ₄₉₅₆₈₃₈₇ = 29.1 to 32.3 dB between individual hours. Lₐₑₗₕₚ₃₉₄₃₇₉₈₉₉₆₉₈₅₂₉₈₂₂ = 49.8 dB in all hours for all exposure conditions.

Procedure/Study Design

Subjects slept for 6 nights in the sleep laboratory, a habituation night followed by a control night followed by 4 exposure nights. Lights out was at 23:00 each evening, and they were awoken by an alarm call each morning at 07:00. They were prohibited from sleeping at any other times, drinking alcohol during the study period and consuming caffeine after 15:00. Sleep patterns were monitored using polysomnography (PSG) and electrocardiography (ECG), recorded using appropriate electrode placements and filter and sampling frequencies [14].

Questionnaires were developed to assess subjective sleep, tiredness, stress and emotional state. A morning questionnaire was administered immediately following awaking and included questions on sleep quality rated on both an 11-point numerical and 5-point semantic scale, how rested/tired, relaxed/tense and irritated/glad they felt, estimated time to fall asleep and number of awakenings, how easy/difficult it was to fall asleep, whether sleep was better/worse than usual and if their sleep was deep or shallow. These were followed by questions specifically relating to how disturbed they were by vibration and noise during the night. The questionnaire concluded with sections to assess mood [15] and stress/energy [16].

Exposure nights were a combination of vibration level (high H or moderate M, Table 1) and traffic intensity (low intensity 20, high intensity 36), giving nights with noise and moderate vibration for 20 trains (NVm20), noise and moderate vibration for 36 trains (NVm36), noise and high vibration for 20 trains (NVh20) and noise and high vibration for 36 trains (NVh36). The noise signals for each train were not changed between nights with different vibration amplitudes. Order effects were minimised by arranging exposures in two identical consecutive Latin squares. Participants of different gender and noise sensitivity were distributed as evenly as practically achievable over the different exposure orders.

The recorded PSG data was analysed by a trained sleep technician. Each 30 s period (known as an epoch) of the recording time (23:00 – 07:00, total 960 epochs per night) was manually examined and assigned a sleep stage based on the EEG, EOG and EMG signals. The sleep stages assigned were either where the person was awake (stage W), in rapid eye movement sleep (stage REM) or in one of three non-REM stages; N1, N2 and N3. Stage N3 is also known as slow wave sleep (SWS) because of the characteristics typifying the EEG signals present in this stage. Identification of EEG arousal – abrupt shifts in the frequency of the EEG signal lasting at least 3 s that can occur within any sleep stage [14] – was performed according to the American Sleep Disorders Association [17]. The recorded PSG data was analysed such that arousal start time and duration were identified.

Analysis

Questionnaire data was analysed using SPSS v. 18 (SPSS Inc., IL, USA). Analysis was performed using ANOVA for repeated measurements and Bonferroni-corrected post-hoc analysis.

A number of parameters were calculated regarding the macrostructure of sleep in the different experimental nights and also for event-related (ER) EEG and heart rate reactions. The scored PSG data was used to determine
total time in bed (TIB, mins), sleep onset latency (SOL, mins), total sleep time (TST, mins), sleep period time (SPT, mins), sleep efficiency (SE, %), wakefulness after sleep onset (WASO, mins), REM and SWS latency (mins), total number of EEG arousals and total number of awakenings, total number of sleep stage changes (SSC) to a lighter stage, first awakening after SOL (mins), maximum continuous duration in SWS and REM (mins) and the total percentage of sleep spent in each sleep stage (N1, N2, N3, REM). For the calculation of SSCs, REM was considered as the ‘lightest’ sleep stage, followed by N1, N2 and N3 respectively in accordance with Carter et al. [18]. Changes to Wake were not considered as an SSC but were instead treated separately as awakenings. Possible changes are therefore (Initial stage – Lighter stage): N1 – REM, N2 – REM, N2 – N1, N3 – REM, N3 – N1 and N3 – N2.

The probability of a single train evoking an EEG reaction, an arousal or awakening, was determined by scanning a time window of 60 s from event onset in the manner described by Basner et al. [19]. A similar algorithm was applied to analyse ER SSCs, with the initial sleep stage being designated by the first epoch influenced by at least 15 s of an exposure. Where this was not possible due to short duration trains, the epoch affected by the majority of an event was used to determine initial sleep stage. Event-related alterations in heart rate were determined using an approach advocated previously [19,20].

RESULTS

Subjective Data

No overall effect of exposure was found on subjectively rated sleep quality (Figure 1). No effects of exposure order were found. There was a significant interaction of gender *exposure (p=0.008) with no significant main effect of gender. Post-hoc testing revealed that males had a significantly higher sleep quality than females in the control night (p_{bonf-corr}=0.04).

![Figure 1. Mean rating of sleep quality during control and exposure nights, recorded immediately after awakening.](image)

Error bars indicate single standard deviation. No significant effect of exposure on sleep quality was found.

There was a significant linear interaction of noise sensitivity *exposure (p=0.017) with no significant main effect of noise sensitivity. Post-hoc tests showed that sensitive persons had a lower sleep quality than non-sensitive in the NVh36night (p=0.023), although this effect did not remain significant after Bonferroni-correction.

A significant effect of exposure (p=0.01) was found on the perceived disturbance from vibrations (Figure 2A). For each of the experimental nights, participants reported higher disturbance by vibrations compared to the control (p_{bonf-corr}<0.01). Furthermore there was a significant effect of the number of trains (p=0.047), whereby participants were more disturbed by the higher number of trains. There was no significant main effect of gender or gender*exposure interaction. There was a significant main effect of noise sensitivity (p=0.001) but no significant noise sensitivity*exposure interaction.

There was a significant effect of exposure on the perceived disturbance by noise (p=0.003, Figure 2B). For each of the experimental nights, participants reported higher noise disturbance noise compared to the control night (p_{bonf-corr}=0.01). Furthermore there was a tendency for the number of trains to have an impact on noise
disturbance (p=0.052). There was no significant main effect of gender and no significant gender*exposure interaction. There was a significant main effect of noise sensitivity (p=0.001) but no significant noise sensitivity*exposure interaction.

![Figure 2. Mean rating of sleep disturbance from vibration (A) and noise (B) during the experimental nights, recorded immediately following awakening. Error bars show single standard deviation.](image)

For the variable never woke – woke often a significant main effect of exposure was reported (p=0.028). Post-hoc testing revealed that participants reported to wake up more often in the high number of train nights compared to the low (p=0.001). There was no significant effect of vibration amplitude. There was a significant main effect of noise sensitivity (p=0.023), with noise-sensitive persons reporting to wake up more often than the non-sensitive group. Furthermore, a significant gender*exposure interaction was found (p=0.044). Post-hoc testing revealed that females reported to wake up more often than males in the control night (p=0.012) although this did not survive Bonferroni-correction.

For the estimated number of wakeups a significant main effect of noise sensitivity was observed (p=0.018). Noise-sensitive persons reported more wake-ups than non-sensitive persons. Furthermore, a significant gender*exposure interaction was found (p=0.046). However post-hoc tests revealed no significant effect for any of the individual nights.

For the variable slept better – slept worse than usual a significant gender*exposure interaction was found (p=0.007). Post hoc test revealed that for the control morning males more often report to have slept better than females (p=0.021), although this effect did not survive Bonferroni-correction.

For the slept deep – light parameter a significant main effect of noise sensitivity was observed (p=0.044). Noise-sensitive persons reported lighter sleep than the non-sensitive group. Furthermore, a significant gender*exposure interaction was found (p=0.007). Post-hoc tests revealed that females reported lighter sleep then males in the control night (p_{bonf-corr}=0.005).

**Physiological Data**

Due to a technical fault, PSG recordings were not obtained for a single participant in the NVh20 condition (noise-sensitive female). No other procedural problems were encountered.

Statistically significant effects were found for sleep latency, total number of SSCs, WASO, and maximum uninterrupted time spent in stage N3. The effect on first awakening just misses significance (p_{corr}=0.051). Additionally, a tendency is observed for the percentage of time asleep spent in N1, N2 and REM and for the number of EEG arousals.

For illustrative purposes the average number of ER awakenings and arousals per participant in each exposure night is shown in Figure 3. It indicates that compared to the baseline data acquired during control nights the number of awakenings and arousals are higher for the higher number of trains and higher amplitude conditions.
Similarly, the amplitude of ER increase in heart rate was found to be significantly influenced by the vibration amplitude (p<0.01) although this was irrespective of event frequency.

![Figure 3. Average number of event-related awakenings (A) and arousals (B) in each exposure night. Baseline values are calculated by introducing 36 phantom events in the control night and performing the same event-related analysis as applied in exposure nights.](image)

**DISCUSSION**

The data was obtained using young, healthy subjects so caution should be taken in applying the results to a wider population. In the control night which was always the second night spent in the laboratory, females reported lower sleep quality and lighter sleep. This suggests that males habituated to the environment and experimental setup more quickly, which conflicts with previous work finding that a single night of habituation is adequate for polysomnography lab trials [21].

Little guidance exists today on how vibration sensitivity should be assessed. Noise sensitivity has been previously shown to be correlated with daytime noise annoyance the subjective evaluation of sleep [22,23]. The questionnaire data obtained in our study shows that noise-sensitive persons report a higher degree of disturbance for both vibration and noise exposure, even though the majority of the night is spent in an unconscious sleeping state. This suggests that the 5-point semantic scale used to discriminate between sensitive and non-noise sensitive persons may provide a useful indication of the impact of vibration although this cannot be said for certain with the current study design. Such a conclusion would need to be confirmed by including noise-free vibration exposure nights.

The noise exposure was identical for the NVm36 and NVh36 conditions, whereas the vibration amplitude was increased. The larger number of ER awakenings in the latter case suggests that vibration exposure has the potential to contribute towards fragmented sleep. This is supported by the same observed pattern between the NVm20 and NVh20 conditions. This is of importance given that PSG awakenings are often considered to be the strongest form of reaction to an environmental exposure, such as road traffic noise, an aeroplane flyover or a train passby [24]. However, the total number of awakenings over the full night did not significantly change with exposure. Similarly, the number of event-related EEG arousals was higher in nights with stronger vibration although over the full night there was only a tendency for the total number of arousals to increase. The implication is that these ER reactions occur at the expense of spontaneous awakenings and arousals, supporting previous work by Basner et al. [19].

The probability of an individual event causing a change to a lighter sleep stage was related to the vibration amplitude, and the total number of SSCs during the night was higher in both the NVm36 and NVh36 conditions compared to the control, meaning that the macrostructure of sleep is not preserved in the same manner seen for the case of EEG reactions. Although the probability of an ER SSC was higher for the stronger vibrations, it cannot be said at this point whether the increase is due to the body reacting to the vibration, or if there is a cross-modal effect whereby the increased vibration lowers the threshold of a SSC due to noise. Additionally, the shortest continuous N3 duration occurred in NVh36 as did the first awakening.
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