Euronoise 2018
Crete

The effects on sleep of ground borne noise from trains in tunnels

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Summary
In residential areas around railway tunnels, there is no direct airborne noise from the railways, but residents may be exposed to ground borne noise. Nocturnal airborne railway noise has been shown to be potentially disruptive to sleep, but there is only limited previous research on the effects of ground borne railway noise. Here we present laboratory studies investigating how ground borne railway noise at levels occurring in the field impacts on sleep.
Data on sound pressure level, duration and frequency content of ground borne noise from railways were collected from the scientific literature, from measurement reports and by renewed measurements at a few locations in Stockholm, Sweden. Using these data as input, the exposures for the sleep studies were synthesised to represent the variation seen in the gathered data. An initial pilot study (n=5) investigated possible differential effects of frequency content and duration (passenger vs. freight trains). Data from the pilot study implicated very low frequency train passages as potentially disruptive for sleep. The following main study (n=23) therefore further examined frequency content, and additionally examined the effect of noise level. Across both studies, young and healthy individuals spent five nights in a laboratory furnished to resemble an apartment. The first night was for adaptation to the study setting. The following four nights included a single quiet night to obtain baseline sleep, and three exposure nights involving synthesised ground borne noise from passenger and freight trains. Effects on sleep physiology and self-reported sleep outcomes were obtained using polysomnography and questionnaires respectively, although physiologic outcomes from the pilot only are herein reported.

PACS no. 43.50.Qp, 43.50.Rq, 43.50.Lj

1. Introduction

Sleep serves a number of vital functions, which may include reduced energy consumption [1], synthesis of proteins and lipids in preparation for wakefulness [2], reducing cellular stress [3], restoration of cognitive performance degradation [4], synaptic pruning [5] and consolidation of memories [6]. Sufficient quantity and quality of sleep are therefore important in maintaining good health and wellbeing. However, sleep is by definition reversible, and can be disturbed by external stimuli including noise. Noise during sleep can lead to primary effects, including cortical and autonomic response and hormone release [7]. These physiologic responses can then lead to impaired performance and a decrease in the subjective assessment of sleep quality in the short term. In the long-term, there is some evidence for nocturnal noise exposure leading to the development of illness, particularly acute cardiovascular disease [8].

Previous research into the effects of noise from railways in tunnels has used only self-reported measures of sleep disturbance [9]. Self-reports of noise-induced annoyance and sleep disturbance were related to the modelled maximum noise level of structurally reradiated noise from railway tunnels [9]. In this sample of 313 persons, the percentage of respondents reporting noise-induced problems falling asleep and awakenings was around 3% and 4% respectively.

Sleep, because of the unconscious state it engenders, is difficult to retrospectively self-assess. Accordingly, the agreement between objectively measured sleep and self-reported measures of sleep quality and disturbance can be poor [10]. Physiologic response of which one is unaware may still be potentially deleterious for health and wellbeing, so objective sleep measures are needed. We therefore investigated the impact of ground borne noise from trains in tunnels using both electrophysiological and self-reported measures of sleep.

2. Methods

An initial noise survey of ground borne noise from trains in tunnels was conducted to inform on typical exposures in the surrounding residential areas. These measurements formed the basis of the design of different noise scenarios. These scenarios were used as exposures in two laboratory studies, performed to investigate the objective and subjective effects of the noise on sleep.

2.1. Exposure assessment

At the beginning of the project a literature survey was performed on structure-borne noise from railway tunnels. The main focus was to find published spectra and time histories from different measurements in dwellings above tunnels. We found frequency spectra in four publications [9, 11-13]. A recent overview report in Swedish contains examples of measurements in Sweden from a few sites for third octave bands from 50 to 630 Hz [14]. We were also able to obtain raw data from four sites in Sweden by directly contacting either the consultants that performed the measurements or other involved parties.

In addition to obtaining previous data, we furthermore performed two sets of measurements in Stockholm. One site was located in a building over a subway tunnel, and the other over a conventional railway tunnel. The measurements were performed with a three microphone setup including a corner position. For the conventional rail tunnel both freight and passenger trains at different speeds were measured.

Looking at all the data collected from the various sources above, both in time and frequency domain, we came to the following conclusions:

1) Noise levels in third octave bands below 50 Hz are often very uncertain. When background data are available, there is almost no signal to noise ratio.

2) Onset rates are difficult to estimate since the overall signal to noise ratio is low, the typical range being 5–15 dB/s.

3) The spectral shape varied greatly in the material, from almost flat spectra to at most 4 dB roll off per third octave band.

Using a theoretical framework for estimating ground borne noise indoors [15], we synthesised audio for typical Swedish freight and passenger trains at different speeds and tunnel depths. The synthesised audio was compared to original recordings by listening in a laboratory environment, and after adjustments the most relevant sounds were used in the sleep experiments (see section 2.4).

2.2. Study setting and protocol

Two sleep studies were performed. The first was a pilot study designed to provide input into the choice of noise exposures in a subsequent larger, main study.

Participants spent five consecutive nights in a sound environment laboratory furnished to resemble a typical apartment [16]. The first night was for adaptation to the unfamiliar setting and the sleep measurement apparatus. The following nights were a quiet control condition and three nights with exposure to ground borne noise. In the pilot, the second night was always the control condition, followed by the three exposure nights in a randomised order. In the main study, the position of the control night was also randomised with the exposure nights, such that it was the second night for seven (30%) and the final night for six (26%) participants. Ground borne noise from was introduced in each exposure night, with forty eight trains per night in pilot and thirty two trains per night in the main study (see section 2.4).

Participants were instructed to start trying to fall asleep at 23:00 each evening, were woken with an alarm call at 07:00 each morning, and were prohibited from sleeping outside of these times. They were free to follow their normal daytime routine, but were required to arrive at the laboratory by 20:00 each evening to allow time for relaxation and setup of the sleep measuring equipment (see section 2.6). Caffeine was prohibited after 15:00 each day, and alcohol was prohibited at all times.

The study was approved by the regional ethical committee at the University of Gothenburg. Participants were financially compensated, provided informed written constant and were free to discontinue in the study at any time.

2.3. Sleep study participants

A summary of the participants is given in Table I. All participants were in good self-reported health, maintained good sleep hygiene (including no medication with potential side effects on sleep) and kept typical sleep and wake times in close agreement with the times scheduled in the study. Hearing was assessed with pure tone audiometry to a screening level of 15 dB HL. Individuals rating themselves as "*quite*", "*very*" or "*extremely*" sensitive to noise on a 5-point semantic scale were coded as noise sensitive. Ratings of "*not at all*" or "*not particularly*" sensitive and were coded as non-sensitive.

Table I. Demographics of study participants. M±SD (mean ± standard deviation).

Study	**n**	**Age (M±SD years)**	**Sex (n women)**	**Noise sensitive (n)**
Pilot	5	22.2±3.0	3	4
Main	23	23.7±4.3	12	6

2.4. Experimental exposures

Based on the noise surveys, representative exposures for ground borne noise of train passages in tunnels were synthesised. Previous research has suggested that self-reported sleep disturbance by noise from railway tunnels may begin to manifest somewhere around ≥42 dB $L_{AF,max,indoor}$ [9]. We used this value as an indication of the noise levels warranting investigation in in the sleep study. The resulting noise levels in the present study, along with other pertinent acoustical data, are given in Table II.

Table II. Acoustical parameters of exposure nights. Measurements at pillow position. Onset rate was dependent upon the train type. T1: Passenger in pilot, LF in main; T2: Freight in pilot, HF in main.

Study	Night	$L_{AEq,23\text{-}07}$ (dB)	$L_{AF,max}$ (dB)	Onset rate (dB/s) T1	Onset rate (dB/s) T2
Pilot	A	21.2	40	14.5	5.4
	B	20.9	40	12.5	8.8
	C	207	40	13.5	9.2
Main	X	18.5	35	11.6	11.7
	Y	19.7	40	11.6	11.7
	Z	22.1	45	11.6	11.7

In the pilot, the train noise spectrum was varied across experimental nights. Night C events were predominantly low frequency (LF), Night A events had the least LF, and Night B fell between the two (Figure 1). For each spectrum, two time histories corresponding to measured passenger and freight train passages were used (Figure 2). Each train type was presented twelve times at two different amplitudes (35 or 40 dB $L_{AF,max}$), thus there were 2 train types × 2 amplitudes × 12 times = 48 trains per night.

In the main study, the train noise spectrum was not varied between exposure nights, but the noise level was changed (Table II). There were two different train spectra within each night, one with dominant LF and one with less LF and more high frequency (HF, see Figure 3). The time history of both the LF and HF trains was deliberately held similar (Figure 4). Each train was presented sixteen times, thus there were 2 train types × 16 times = 32 trains per night.

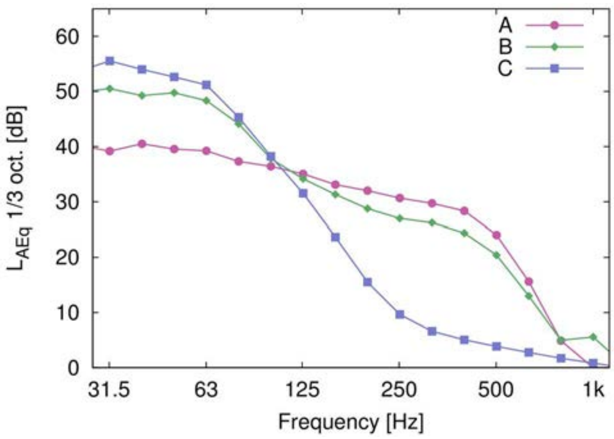

Figure 1. Pilot study noise exposure spectra.

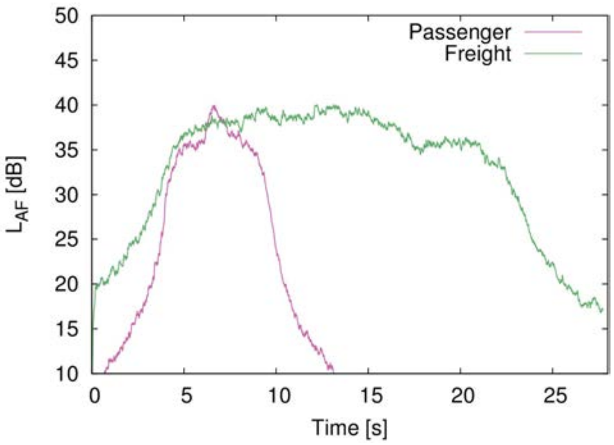

Figure 2. Pilot study noise exposures time histories.

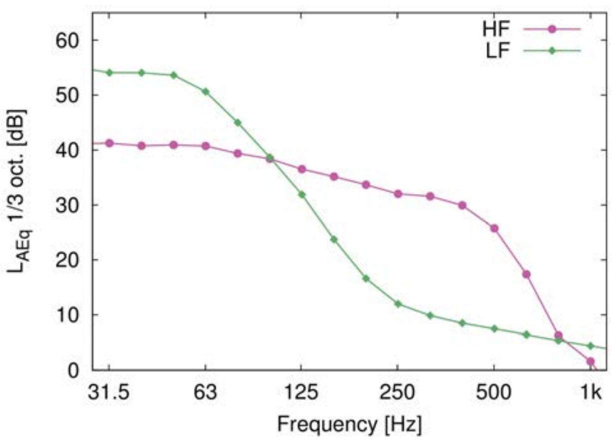

Figure 3. Main study noise exposure spectra. HF/LF: High/Low frequency.

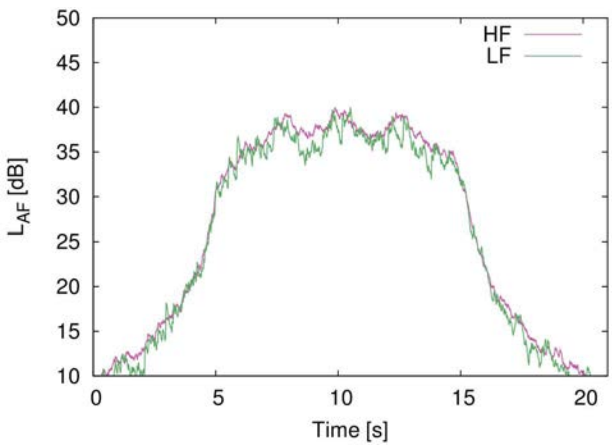

Figure 4. Main study noise exposure time histories. HF/LF: High/Low frequency.

2.5. Questionnaires

Questionnaires were completed each morning within 15 minutes of awakening. A complete description of the questions is given elsewhere and are only summarised here [17]. The following measures were assessed via 0-10 point numerical scales: sleep quality, tiredness, tension, irritation, difficulty sleeping, sleeping worse than usual, perceived sleep depth, awakening frequency and sleep disturbance by noise. A number of measures used five-point semantic response scales: sleep quality, noise-induced poor sleep, noise-induced awakenings, noise-induced difficulty sleeping and noise-induced tiredness. There were also items on the number of recalled awakenings and perceived sleep latency.

2.6. Sleep registration

Electrophysiological sleep was recorded using polysomnography in accordance with current guidance [18]. Sleep staging was performed manually by a single trained sleep technologist who was blind to the study design. Abrupt changes in the electroencephalogram (EEG) meeting the criteria for classification as arousals [18, 19] were scored as either arousals (3-15 s) or awakenings (>15 s) contingent on their duration. EEG sleep was recorded in the main study but the results are not presented in this paper.

2.7. Statistical analysis

2.7.1. Pilot study

Statistical significance was not expected because of insufficient power due to the low sample size. Instead of statistical hypothesis testing, effect sizes and visual inspection of the data were used to make informed judgements about possible exposure-response relationships to further investigate in the main study.

2.7.2. Main study

Questionnaire data were analysed in a linear mixed model with random intercept, accounting for repeated measurements across individuals. Study night was included as the main predictor variable, controlling for sex and dichotomous noise sensitivity. Semantic questionnaire data were analysed as continuous outcomes. Dependent variables in violation of the model assumptions, determined by visual inspection of the residuals, were square root- or log-transformed as appropriate before analysis. Where significant ($p<0.05$) main effects were found, post-hoc between-night analysis was performed with Bonferroni correction to account for multiple hypothesis testing.

3. Results

The following section summarises the findings of the sleep studies.

3.1. Pilot study

The first exposure night, regardless of its constituent noise scenario, was rated as more subjectively disturbing than other exposure nights. Night C was never the first exposure night, and Night B was never the final night. If habituation to the exposures occurred during the study periods, a reduced adverse effect in the final nights would be anticipated. Alternatively, an adverse effect in one night would be expected to lead to carry-over effects in the following nights, with improved sleep. Therefore, because of the unbalanced design of the pilot study, no firm conclusions could be drawn regarding the self-reported data.

There was a limited impact of exposure on objective sleep macrostructure. There were some indications that Night C (most LF) was worse than the other exposure nights, for instance with increased time in wake after sleep onset (Figure 5), reduced continuous time and percentage of sleep in rapid eye movement sleep, greater percentage of sleep in N1 ("light") sleep and more arousals overall. However, other data pointed to Night C being better than the other exposure nights, for instance with a shorter sleep latency and longer time between falling asleep and the first awakening.

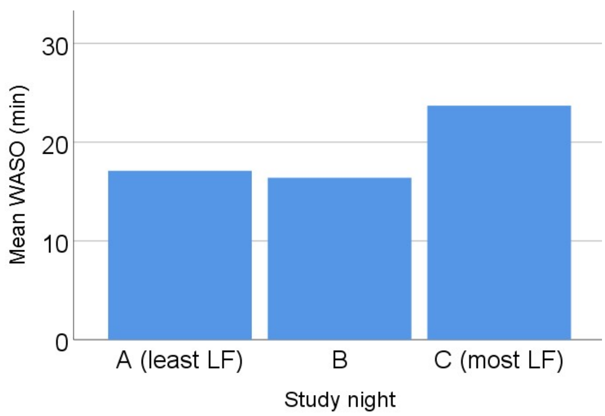

Figure 5 Wakefulness after sleep onset (WASO) in pilot study exposure nights.

The probability of an EEG reaction (arousal or awakening) occurring within 60 s of the start of an event is shown in Figure 6 for the different train types. Data were averaged across all exposure nights (i.e. across all three spectra), and are therefore indicative of response due to differences in onset rate and duration. Relative to spontaneous reaction probability (determined via analysis of sham events in the control night), passenger trains had around a 0.05 higher probability of evoking a reaction.

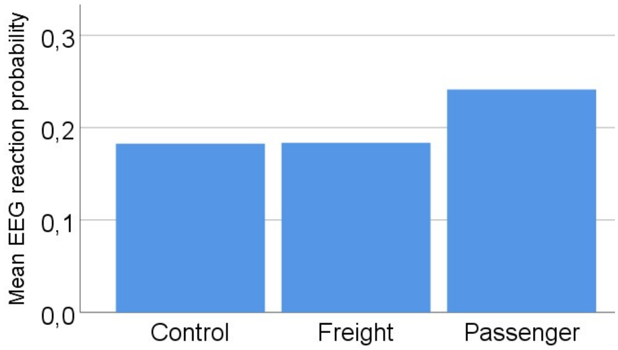

Figure 6. Event-related probability of observing an EEG arousal of awakning in a 60 s window following train onset. Data are averaged across all exposure nights and noise levels.

3.2. Main study

3.2.1. Self-reported data

Statistically significant main effects were found for sleep quality (numerical and semantic), number of recalled awakenings, sleep disturbance by noise, difficulty sleeping, perceived sleep depth, waking frequency, noise-induced poor sleep, noise-induced awakenings, noise-induced difficulty sleeping and noise-induced tiredness.

In all of these cases, sleep was negatively affected by noise exposure, with Night Z ($L_{AF,max}$=45 dB) rated worse than the control night. Night C was also often rated as worse than Night X (6 items: numerical and semantic sleep quality, sleep disturbance by noise, noise-induced poor sleep, noise-induced awakenings and noise-induced difficulty sleeping), and occasionally rated as worse than Night Y (3 items: numerical sleep quality, sleep disturbance by noise and noise-induced poor sleep). Sleep disturbance by noise was rated higher in Night Y than the control. No significant differences were found between Night A and the control. Mean sleep disturbance by noise and sleep quality are presented in Figure 7 as examples of the observed exposure-dependent response patterns.

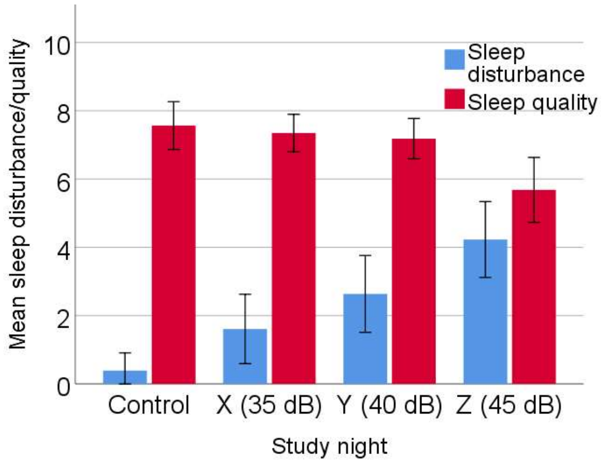

Figure 7. Mean self-reported sleep disturbance by noise and sleep quality across main study nights. Noise levels are $L_{AF,max}$. Error bars indicate 95% confidence intervals.

No effects of noise exposure were found for tiredness, tension, irritation, perceived sleep latency or sleeping worse than usual.

Effects of noise sensitivity were found for tension and sleep depth. In both cases, sensitive individuals rated their sleep as better than the non-sensitive persons (more relaxed/less tense in the morning and deeper sleep).

No effects of sex were found for any outcomes.

4. Discussion

This paper presents a study into the effects of railway noise from tunnels on sleep, examined for the first time in a controlled environment and with physiologic measures response.

In the pilot, passenger trains appeared more likely to lead to sleep fragmentation (arousals or awakenings) than freight trains. This may be explained by the higher noise onset rate for the passenger trains, and onset rate of noise events has previously been shown to be an important predictor of instantaneous reaction probability [20].

In the main study, the majority of self-reported sleep measures were deleteriously affected by ground borne railway noise in a dose-dependent manner. Relative to the Control, no differences in self-reported sleep were found in Night X ($L_{AF,max}$=35 dB).,Differences in Night Y ($L_{AF,max}$=40 dB) were found only for sleep disturbance by noise and in Night Z ($L_{AF,max}$=45 dB) differences were found in eleven of the sixteen measures. This suggests that self-reported sleep disturbance by ground borne railway noise manifests somewhere around 40-45 dB, closely agreeing with a 42 dB threshold found in a previous field study [9]. In further support of this, relative to the Control there was a higher probability of event-related EEG arousals in Night Z, but probabilities in Nights X or Y did not significantly differ (data not shown). At noise levels above those examined in the present study, an increase in adverse effects would be anticipated, as is generally seen for other environmental noise sources [21].

Noise sensitive persons reported deeper sleep and lower tension than non-sensitive counterparts. This is a surprising result since sensitive individuals have generally previously been found to report worse sleep [22]. However, the current study was not designed to examine underlying differences between sensitivity groups, and hence included only six individuals classified as noise sensitive. This small sample may not be representative of sensitive individuals in the wider population, particularly since only study applicants with good sleep were accepted.

Continuing from the final point of the previous paragraph, it was not only sensitive individuals that had good normal sleep, but also the non-sensitive group. The study sample may therefore represent a population particularly resilient to external influences on sleep, who may have reacted less strongly to the noise exposure than individuals of different ages or with pre-existing sleep problems. Conversely, populations exposed to noise at home may partially habituate over time, having fewer arousals, awakenings and sleep stage changes [23], or at least become accustomed to poor sleep and consequently upwardly adjust their perceived sleep quality [24], and may be less affected than the group in the present study.

Conclusions

Ground borne noise from railways in tunnels generally had a negative effect on self-reported sleep, with the majority of self-reported measures worse following nights with 45 dB $L_{AF,max}$ trains than in quiet control nights. Fewer adverse effects were seen at lower noise levels. Ongoing work will determine whether the observed self-repotred outcomes correspond to underlying adverse physiologic sleep effects.

Acknowledgement

This project was funded by Trafikverket, the Swedish Transport Administration. We thank Hanna Hertzberg and Lovisa Lyngfelt for assistance in performing the study.

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