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PHYSIOLOGICAL REACTION THRESHOLDS TO VIBRATION DURING SLEEP

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Vibrationsnivåer som framkallar fysiologisk reaktion under sömn

Ljud och vibrationer från tågtrafik kan störa sömnen hos boende nära järnvägen. För buller har man tidigare undersökt vid vilken lägsta nivå som fysiologiska reaktioner kan mätas under sömnen. De reaktioner man har undersökt är uppvaknanden och fragmentering av sömnen. Världshälsoorganisationen (WHO) sammanställde under 2009 forskningen på detta område och anger att mätbara effekter startar kring 35dB mätt som maximal A-vägd ljudtrycksnivåer med tidsvägning Fast.

Det saknas motsvarande kunskap för vibrationer. För att undersöka detta genomfördes sömnförsök i två omgångar i ljudmiljölaboratoriet vid Arbets- och miljömedicin, Sahlgrenska akademien. Först genomfördes ett pilotförsök med fem försökspersoner för att avgöra ungefär kring vilken vibrationshastighet som man börjar se effekter. Denna kunskap användes sedan för att bestämma vibrationsexponeringen i huvudförsöket, där totalt 12 personer deltog. Försökspersonerna sov fem nätter i ljudmiljölaboratoriet. Första natten var en tillvänjningsnatt för att prova på att sova i den nya miljön med givare monterade osv. Andra natten var en tyst kontrollnatt, och därefter följde 3 nätter med tågpassager med varierande vibrationshastighet i sängen. Under alla nätter mättes försökspersonernas sömn med polysomnografi (PSG), dvs elektroder monterade på huvudet och kroppen för att mäta EEG (hjärnaktivitet), EOG (ögonsrörelser), EMG (muskelaktivitet) och ECG (hjärtrytm).

Under sömnförsöken exponerades försökspersonerna för vibrationer via ett elektrodynamiskt skakdon som vibrerade sängen i horisontell riktning utmed sängens längsta axel (huvud-fot). Vibrationssignalen var en amplitudmodulerad sinusvåg med frekvens 10 Hz. Som mått på vibrationernas styrka användes den maximala komfortvägda vibrationshastigheten med tidsvägning S, och exponeringen varierades mellan 0,2 och 0,4 mm/s. Komfortvägd vibrationshastighet är det mått som används i Svensk standard (SS 460 48 61) för att utvärdera vibrationer från tågtrafik.

För att inte skapa en orealistisk situation med helt tysta tågpassager, och för att i viss mån maskera mekanisk buller från skakdonen, så spelades en svag bullersignal med maximal bullernivå 30 dB upp under varje tågpassage. Detta är under reaktionströskeln för ljud enligt WHO så det är liten risk att resultaten påverkades av effekter som beror på ljudet istället för vibrationerna.

Totalt 36 tågpassager spelade upp under sömnförsöken och vibrationsnivån varierades för varje passage enligt ett randomiserat mönster, se tabell 3 och 6. Händelserna var jämnt fördelade över natten, och påverkan på sömnen studerades genom att jämföra sömndjup och hjärtfrekvens i de 30 sekunder som föregick starten på tågpassagen med påföljande 60 sekunder.

Förändringar i sömndjup och sannolikheten för att vakna observerades vid 0,3 mm/s, men var statistiskt signifikanta först vi 0,4 mm/s. Vid 0,2 mm/s observerades inga skillnader gentemot kontrollnatten utan vibrationer. Förändringar i hjärtfrekvens var signifikanta både vid 0,3 mm/s och 0,4 mm/s, men syntes inte vid 0,2 mm/s. Tröskelvärdena sammanfattas i tabell 1 tillsammans med motsvarande tröskelvärde för maximal ljudtrycksnivå.

Tabell 1 Tröskelvärde för fysiologisk reaktion under sömn. Bullervärden är från WHO [1], vibrationsvärden är framtagna inom detta projekt.

Effekt	*Buller[1]*	*Vibration*
Förändring i hjärtrytm	Ej undersökt	0,3 mm/s
EEG uppvaknande	$L_{AFmax,inside}$=35 dB	0,4 mm/s
Förändring i sömnstadie och fragmenterad sömn	$L_{AFmax,inside}$=35 dB	0,4 mm/s

Executive summary

The World Health Organization Night Noise Guidelines for Europe 2009 report that there is sufficient evidence for biological effects of noise on sleep, starting at $L_{AF,max,inside}$=32 dB [1]. Alterations in sleep structure and electroencephalogram (EEG) awakenings start to occur at $L_{AF,max,inside}$=35 dB. Changes in cardiovascular activity during sleep also occur as a result of noise exposure, but threshold levels have not been determined. Noise from freight trains in particular has been found to cause more frequent awakenings [2] and stronger cardiac response [3] than passenger trains. In the field, freight trains are often accompanied by low frequency vibration, with amplitudes commonly around 0.4 – 1.5 mm/s (comfort weighted [4]) near railway lines [5]. As with noise, moderate to high level vibration from freight has been shown to contribute towards cortical EEG reactions and changes of heart rate during sleep [6-8]. However, it is not presently known at what threshold levels physiological effects due to vibration begin to occur.

The research group aimed to identify a physiological reaction threshold to vibration during sleep. An initial pilot study was conducted to give a first indication of where such a threshold might lie. A subsequent larger-scale main study further investigated the vibration level response threshold, and also provided knowledge regarding what physiological response occur at 0.4 mm/s, the current lowest limit value enforced for new railway lines in Sweden [9].

Changes in sleep stage and awakenings were observed at 0.4 mm/s, while indications were seen at 0.3 mm/s but not 0.2 mm/s (see Figure 1). Changes in heart rate were seen at 0.3 and 0.4 mm/s, but not at 0.2 mm/s (see Figure 2). This study found that the physiological effects and threshold levels for these WHO defined effects were 0.3 mm/s for changes in cardiac activity, and 0.4 mm/s for EEG awakenings and changes in sleep structure and fragmentation of sleep (see Table 2).

Table 2 Biological effects and thresholds levels for single-exposure effects during sleep. Noise thresholds are from the WHO Night Noise Guidelines for Europe 2009 [1]. Vibration thresholds as determined in the present work.

Effect	*Threshold, noise[1]*	*Threshold, vibration*
Change in cardiovascular activity	Not determined	0.3 mm/s
EEG awakening	$L_{AFmax,inside}$=35 dB	0.4 mm/s
Changes in sleep structure and fragmentation of sleep	$L_{AFmax,inside}$=35 dB	0.4 mm/s

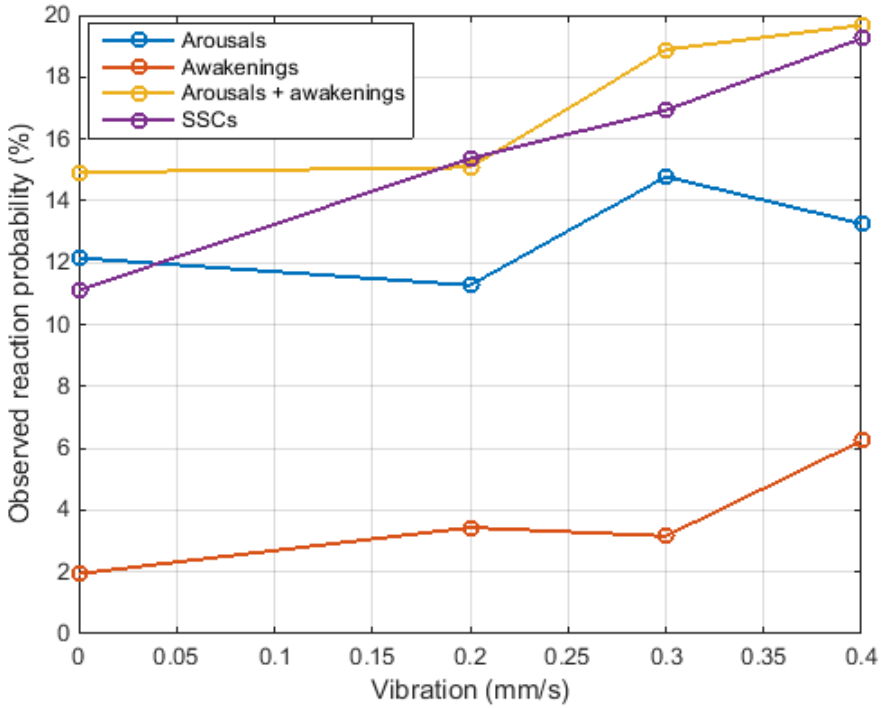

Figure 1 Probability of observing arousals, awakenings, combined EEG reactions and sleep stage changes (SSCs) in the 60s following train onset for different vibration amplitudes. Amplitude=0 mm/s is spontaneous probability obtained from the quiet control night.

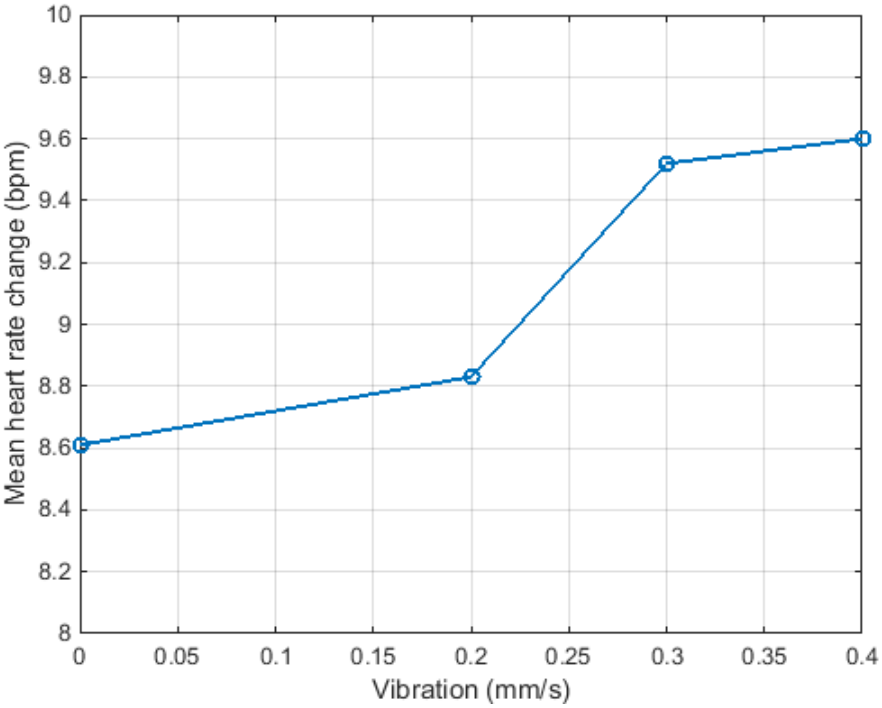

Figure 2 Change in heart rate relative to 10s baseline in the 60s following train onset for different vibration amplitudes. Amplitude=0 mm/s is spontaneous change obtained from the quiet control night.

Glossary of terms

Term	*Definition*
Arousal	Abrupt shift in the measured EEG frequency greater than 16 Hz which occurs during sleep, and is at least 3s in duration , but of insufficient duration to lead to a full awakening.
Awakening	An arousal of sufficient duration (i.e. >15s) for a sleep epoch to be classed as Wake.
A-weighting	Frequency weighting applied to noise spectrum to simulate frequency dependency of human hearing.
BPM	Beats per minute. Measure of heart rate.
Comfort weighting	Frequency-weighting applied to vibration, as used in the Nordic countries. Described in full in Svensk Standard SS 460 48 61[4]. The standard specifies reporting vibration as a frequency-weighted velocity, in terms of maximum root mean square (rms) value with a 1 second time weighting. Unless otherwise specified, all vibration values reported in this document are comfort-weighted.
dB	Decibel. Measure of acoustic noise level.
ECG	Electrocardiogram
EEG	Electroencephalogram
Hz	Hertz, defined as cycles per second. Measure of frequency.
$L_{AF,max,inside}$	Maximum A-weighted indoor noise level, fast (0.125s) time constant
$L_{A,Eq}$	Equivalent A-weighted noise level.
mm/s	Millimetres per second. Measure of maximum root mean square (rms) vibration velocity, using a 1s time constant and is reported using the Nordic comfort weighting (see entry above).
Noise	Airborne sound. In this report generally refers to environmental noise in the home, arising from freight train passages.
PSG	Polysomnography, a technique used to measure sleep physiology
SD	Standard deviation.
Sleep stage	Depth of sleep, measured in 30s epochs. Stage N1 = “light” sleep, Stage N2 = “intermediate” sleep, Stage N3 = “deep” sleep/slow wave sleep, REM = rapid eye movement sleep (“dreaming” sleep), Stage W = Wake
SSC	Sleep Stage Change. Only includes changes to “lighter” sleep.
Vibration	Oscillations of a body forced from a state of equilibrium. In this report generally refers to environmental vibration in the home, arising from freight train passages.
WHO	World Health Organization

Background

The World Health Organization Night Noise Guidelines for Europe 2009 report that there is sufficient evidence for biological effects of noise on sleep, starting at $L_{AF,max,inside}$=32 dB [1]. Alterations in sleep structure and electroencephalogram (EEG) awakenings start to occur at $L_{AF,max,inside}$=35 dB. Changes in cardiovascular activity during sleep also occur as a result of noise exposure, but threshold levels have not been determined. Noise from freight trains in particular has been found to cause more frequent awakenings [2] and stronger cardiac response [3] than passenger trains. In the field, freight trains are often accompanied by low frequency vibration, with amplitudes commonly around 0.4 – 1.5 mm/s near railway lines [5]. As with noise, moderate to high level vibration from freight has been shown to contribute towards cortical EEG reactions and changes of heart rate during sleep [6-8]. However, it is not presently known at what threshold levels biological effects due to vibration begin to occur. These reaction thresholds are defined by WHO as "*the level above which an effect starts to occur or shows itself to be dependent on the exposure level*", and the same definition shall be adopted in this report [1].

Sensory perception thresholds are defined as "the level of a [stimulus] necessary to be just [detectable]" [10], and they are determined using alert study subjects. This differs from the reactions thresholds to a stimulus during sleep, which is the level of a stimulus necessary to induce a response (e.g. awakening, sleep stage change), rather than just being detectable However, perception thresholds provide a useful indication of what the minimum reaction threshold might be. Vibration perception thresholds have been calculated for alert persons in the recumbent position, the same position adopted during sleep [11-13]. In the frequency range of freight vibration, approximately 5–10 Hz, this perception threshold corresponds to a maximum comfort weighted [4] amplitude of around 0.1–0.3 mm/s. ISO 2631-1 states that "*Fifty percent of alert, fit persons can just detect a W_k weighted vibration with a peak magnitude of 0.015 m/s^2*" [14]. At 10 Hz, this corresponds to a comfort weighted velocity of approximately 0.2 mm/s. Assuming that vibration amplitudes for perception and biological effect thresholds would be similar, it was therefore hypothesised that the reaction threshold for vibration during sleep would lie somewhere between 0.1 and 0.3 mm/s.

Methods

The research group aimed to identify a physiological reaction threshold to vibration during sleep. An initial pilot study was conducted to initially identify vibration levels which would initiate a response. This was followed by a larger scale main study to further investigate the vibration level response threshold, and also provided knowledge regarding what physiological response occur at 0.4 mm/s, the current lowest limit value enforced for new railway lines in Sweden [9].

Study design summary

The pilot study involved 5 young, healthy individuals who each spent 5 nights in the sound environment laboratory. They were exposed to vibrations of 0.1, 0.2 and 0.3 mm/s (comfort-weighted) during the night, with 12exposures per night per amplitude. Based on the results of this pilot, a main study was conducted with 16 young, healthy individuals, each of whom spent 5 nights in the laboratory. The vibration amplitudes used in this main study were 0.2, 0.3 and 0.4 mm/s (comfort-weighted), with 12 exposures per night per amplitude.

Study setting

The research group's sound environment laboratory was equipped to resemble an apartment, having a kitchenette, dining area and living space, showers, toilets and a private entrance, more information available at www.amm.se/soundenvironment. The laboratory includes 3 private bedrooms, within each of which is a single bed with an electrodynamic transducer mounted to the underside of the bed frame. These transducers were within enclosures, and were used to introduce the desired vibration during the study nights. Loudspeakers mounted within the ceiling introduced the desired audio during the experiment.

Exposures

The study protocol involved participants spending 5 consecutive nights in the sound environment laboratory. Throughout the study period, artificial background ventilation noise L_{AEq}=25 dB was introduced into the bedrooms. The first night was a period to acclimatise to the experimental setting. The second night was a quiet control night during which normal baseline sleep was measured. Nights 3, 4 and 5 were exposure nights in which vibration exposure was introduced. Thirty six trains were introduced in each exposure night. The vibration signal was an amplitude modulated 10 Hz sinusoid with a rise time from 0 mm/s to the first maximum of 5.6 s. The vibration signal is described in detail elsewhere [15].

Two trains of different durations were used each night, see Table 3, Figure 3 and Figure 4. The train passages are based on measurements performed in Lerum, along the line "Västra stambanan". The average freight train length for the whole network in Sweden is approximately 350 m, but many trains are both shorter and longer; lengths of up to 650 m do occur. The passage time at 90 km/h for a 350 m train is 14 seconds, but the sound and vibration levels increase and decrease as the train approaches and then leaves the reception

point. Additionally, many trains travel slower than 90 km/h. The two train passages used in the experiment represent longer than average passage times, but do occur in real traffic.

Each train presented in Table 3 occurred at 6 instances at 3 different vibration amplitudes. This yields a total of 2 trains × 3 amplitudes × 6 instances = 36 trains per night. This is in line with typical nocturnal timetabling in Sweden, where 26 trains occur between 22-06 in Töreboda and Falköping (3.3 per hour), and as many as 69 occur between 22-06 in Sollentuna (8.6 per hour) [16]. The timing of the different vibration amplitudes was varied over the 3 exposure nights in a Latin square design. Trains started at 23:05:00, 23:15:00 and then subsequently every 13.5 minutes until 06:54:00. Reaction thresholds to noise are dependent upon the sleep stage of the exposed person at the time of exposure [17]. The distribution of sleep stages is not uniform over the course of the night; therefore spreading the vibration exposures over the night increases the likelihood of having different vibration amplitude exposures occurring during all sleep stage.

Vibration was accompanied by low level freight train noise exposure so that study participants could contextualise the vibration source. In order to ensure that any responses observed were due to vibration rather than noise, maximum noise levels of $L_{AF,max}$=30 dB, which falls below the biological reaction thresholds given by WHO, were used (see Table 3).

Table 3 Train characteristics in exposure nights

Train	*Duration (s)*	$L_{AF,max}$ *(dB)*	$L_{A,Eq}$ *(dB)*
1	46.2	30	24.7
2	23.7	30	24.7

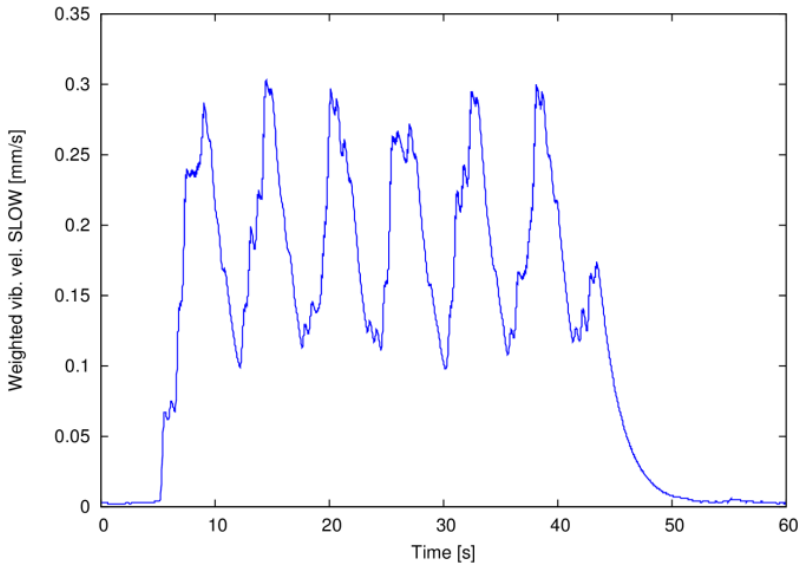

Figure 3 Vibration time history of Train 1 at maximum amplitude of 0.3 mm/s.

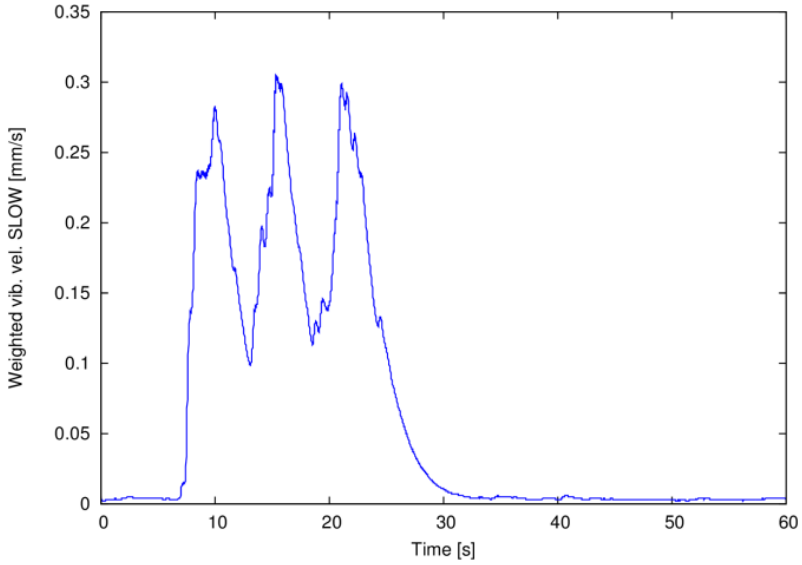

Figure 4 Vibration time history of Train 2 at maximum amplitude of 0.3 mm/s.

Participants

All participants were required to be aged between 18 to 30, be non-smokers and non-snus users, have good normal sleep at home, be free from medication with potential side effects involving impacts on sleep or wakefulness, and have a BMI in the normal range of 18.5 to 25 [18]. Noise sensitivity was assessed using a single item question [7]. Study applicants were asked about their habitual bed time and rise time, and were not considered eligible if these times differed largely from the timings used in the sleep study.

Participants were free to come and go from the sleep laboratory as they wished during the daytime, but were required to arrive at the laboratory by 20:00 each evening to allow sufficient time for relaxation and attachment of the sleep measurement apparatus. They were to begin attempting to fall asleep at lights-out at 23:00, and were woken by an alarm call at 07:00. During the study period they were prohibited from drinking caffeine after 15:00 and alcohol at any time. Each participant was financially compensated for taking part, and provided informed written consent prior to commencement of the study, which was approved by the ethics committee of the University of Gothenburg.

Sleep measurement

Sleep was recorded via polysomnography (PSG) using surface EEG electrodes to register electrical brain activity, EOG to measure eye movements and submental EMG to record muscle tone. Electrode positions, impedances and sampling and filter frequencies were all in accordance with current guidelines [19]. Data were recorded offline onto an ambulatory PSG device (SOMNOscreen plus PSG+, SOMNOmedics, Germany), and analysed by a trained sleep technologist to identify sleep stage in 30s epochs and presence of EEG arousals [20]. Such EEG arousals are thought to be good indicators of sleep fragmentation, rather than only shortening of sleep. Arousals are 3-15s in duration, and are typified by “abrupt shifts in EEG frequency, which may include theta, alpha and/or frequencies greater than 16 Hz” [20].

Arousals which were longer in duration than half a single epoch, i.e. >15s, were classified as awakenings.

Cardiac activity was recorded using a single modified electrocardiograph (ECG) Lead II. ECG electrode placement and sampling and filter frequencies were in accordance with current standards [19].

Analysis

Macrostructure

The cumulative 8-hour vibration exposure was identical during all 3 exposure nights, although the distribution of the different individual exposures was varied between nights. Since the full-night exposure did not change between nights, measures of the full night itself, including sleep macrostructure and self-reported data, are not reported here.

Event-related PSG

A computer routine was developed to determine whether exposure to any given train event was associated with a cortical response. In the routine, events where the participant was already awake were excluded.. A 60s time window following the start of each train event was screened for the occurrence of an EEG arousal or awakening. The sleep stages in the three 30s epochs following train start were compared to the epoch immediately preceding train start to determine if a sleep stage change (SSC) to a less deep stage occurred. Changes to wake stage were not included, and rapid eye movement (REM) sleep was defined as the lightest stage for the purpose of analysis [21].

The prevalence of event-related arousals, awakenings and SSCs was used to calculate the probability of them being associated with train events of different vibration amplitudes. The control period was analysed at 36 time intervals corresponding to the times that trains would occur in the exposure nights. The resulting probabilities were the likelihoods of the reactions occurring spontaneously, in the absence of any stimulus.

Heart rate

A heart rate baseline was obtained by averaging 1s ECG samples in the 10s time window preceding the start of each train. This baseline was subtracted from the maximal heart rate occurring in the 60s time window following the start of each train to yield the maximum event-related heart rate change. Events where the participant was awake during the start of the train, or awoke during the train pass-by, were excluded from the analysis.

Statistical analysis

The event-related probabilities for each level of amplitude were compared to the spontaneous probability from the control condition in a generalised linear mixed model. Vibration amplitude was included as a fixed effect, and study participant was included as a random effect. Dunnet corrections were applied to the p-values, and the level of statistical significance was set at $\alpha=0.05$. Heart rate data were square-root transformed before analysis to account for their non-normal distribution.

Pilot study

Exposures

Vibrations of 0.1, 0.2 and 0.3 mm/s maximum velocity with 1s time weighting were used (Swedish comfort weighting [4]). Each amplitude was introduced 12 times during each night, see Table 4.

Participants

Six healthy participants were originally recruited, but one person dropped out after the habituation night. As per the selection criteria for the pilot study, the remaining 5 participants (2 females and 3 males, mean age 23.2 SD±3.4 years) rated themselves as not being sensitive to noise.

Results

Data were unavailable from a single exposure night in both weeks due to a technical issue. Data were therefore available from 10 participant exposure nights. The total number of observed event-related EEG arousals, awakenings and SSCs from these 10 nights for each vibration amplitude is presented in Table 5

Over 3 exposure nights the participants were exposed to vibrations with maximum amplitudes of 0.1, 0.2 and 0.3 mm/s. The mean probabilities of observing an arousal, awakening or SSC in the 60s following train start are presented in Figure 5. No awakenings were observed during the analysis periods in the control night, therefore it was not possible to determine the spontaneous awakening probability. Awakenings were therefore not investigated in the following analysis. Relative to the control condition, there are significantly higher probabilities of observing arousals ($p=0.007$) and SSCs ($p=0.02$) during 0.3 mm/s vibrations. No significant effects were seen at 0.1 or 0.2 mm/s.

The total number of events analysed in the heart rate analysis after excluding wake stages immediately prior to, or occurring during, trains is given in Table 6. The maximum change in heart rate relative to baseline during the 60s following train start, averaged across all participants, is given in Figure 6. Relative to the control, no significant effects on heart rate were observed following 0.1, 0.2 or 0.3 mm/s vibrations.

Table 4 Exposure start times and amplitudes in the pilot study three exposure nights

Event number	*Train*	*Start time*	*Amplitude (mm/s)*		
			Night A	*Night B*	*Night C*
1	1	23:05:00	0.1	0.2	0.3
2	2	23:15:00	0.2	0.3	0.1
3	1	23:28:30	0.2	0.3	0.1
4	2	23:42:00	0.3	0.1	0.2
5	1	23:55:30	0.3	0.1	0.2
6	2	00:09:00	0.1	0.2	0.3
7	2	00:22:30	0.2	0.3	0.1
8	1	00:36:00	0.2	0.3	0.1
9	2	00:49:30	0.3	0.1	0.2
10	1	01:03:00	0.3	0.1	0.2
11	2	01:16:30	0.1	0.2	0.3
12	1	01:30:00	0.1	0.2	0.3
13	1	01:43:30	0.2	0.3	0.1
14	2	01:57:00	0.3	0.1	0.2
15	1	02:10:30	0.3	0.1	0.2
16	2	02:24:00	0.1	0.2	0.3
17	1	02:37:30	0.1	0.2	0.3
18	2	02:51:00	0.2	0.3	0.1
19	2	03:04:30	0.3	0.1	0.2
20	1	03:18:00	0.3	0.1	0.2
21	2	03:31:30	0.1	0.2	0.3
22	1	03:45:00	0.1	0.2	0.3
23	2	03:58:30	0.2	0.3	0.1
24	1	04:12:00	0.2	0.3	0.1
25	1	04:25:30	0.3	0.1	0.2
26	2	04:39:00	0.1	0.2	0.3
27	1	04:52:30	0.1	0.2	0.3
28	2	05:06:00	0.2	0.3	0.1
29	1	05:19:30	0.2	0.3	0.1
30	2	05:33:00	0.3	0.1	0.2
31	2	05:46:30	0.1	0.2	0.3
32	1	06:00:00	0.1	0.2	0.3
33	2	06:13:30	0.2	0.3	0.1
34	1	06:27:00	0.2	0.3	0.1
35	2	06:40:30	0.3	0.1	0.2
36	1	06:54:00	0.3	0.1	0.2

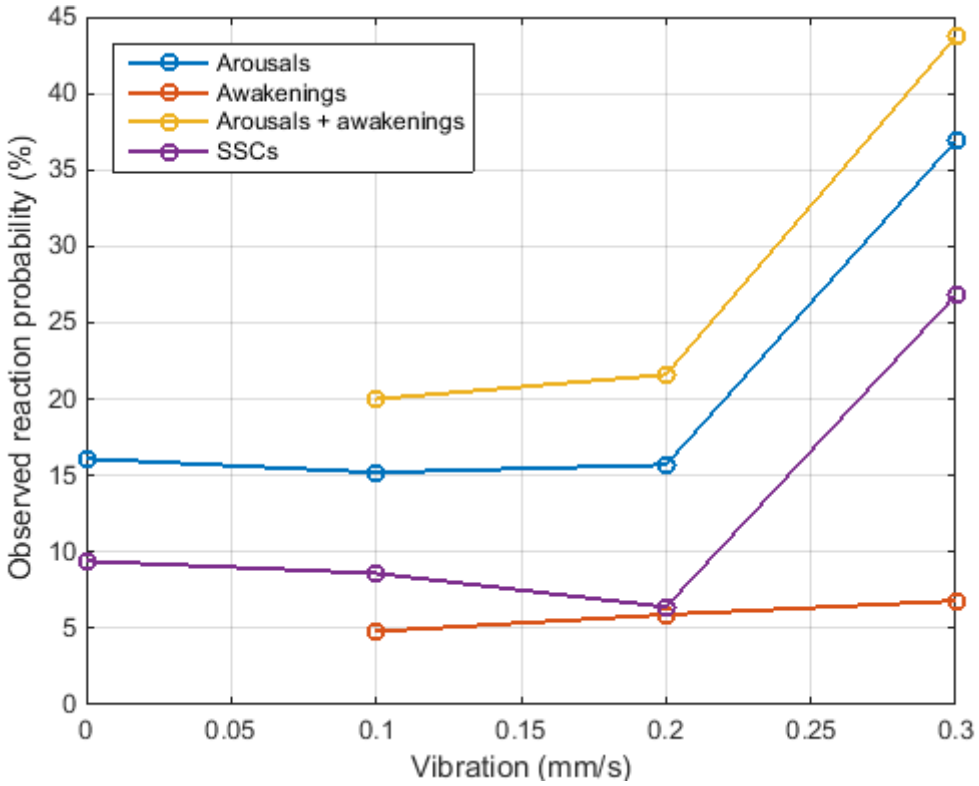

Figure 5 Event-related cortical outcomes from the pilot study. SSC = Sleep Stage Changes to a lighter stage. No awakenings were observed during the analysed time periods in the control night (0 mm/s).

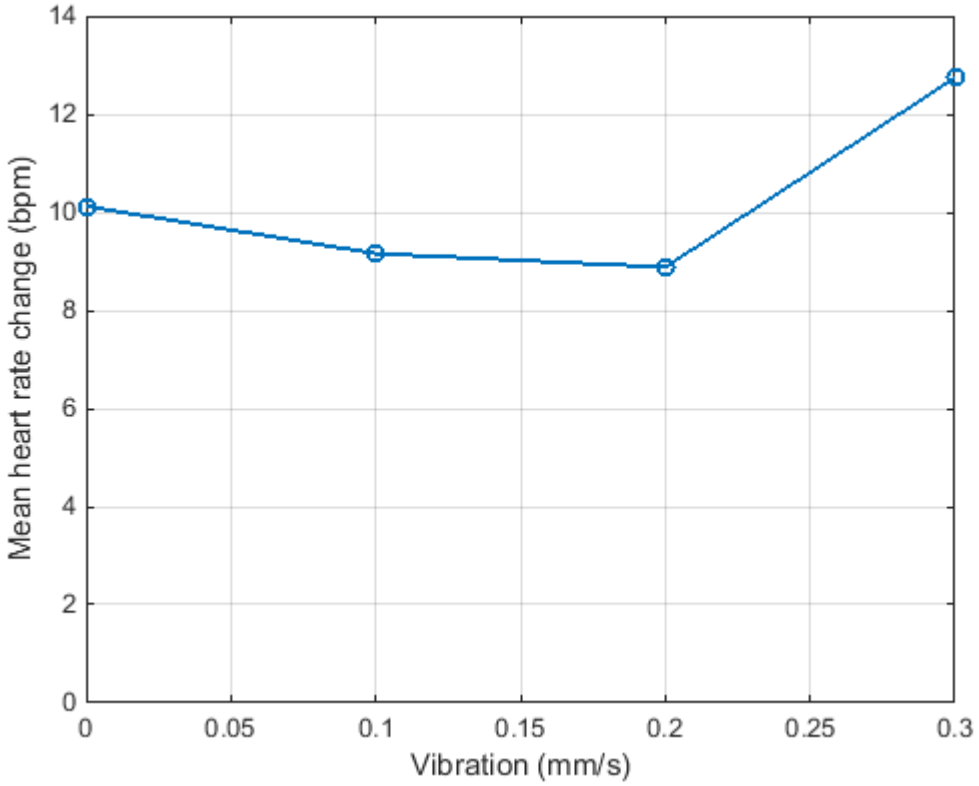

Figure 6 Change in heart rate relative to 10s baseline in the 60s following train onset for different vibration amplitudes in the pilot study. Amplitude = 0 mm/s is spontaneous change obtained from the quiet control night.

Table 5 Total number of observations of event-related cortical reactions used in probability calculations.

Amplitude (mm/s)	*Arousals (n)*	*Awakenings (n)*	*SSCs (n)*
Control	26	0	12
0.1	16	5	7
0.2	16	6	5
0.3	38	7	22

Table 6 Number of event-related samples used in heart rate change calculations. Events involving wake periods have been excluded.

Amplitude (mm/s)	*Total events (n)*	*Samples (n)*	*Excluded (n)*
Control	5*36=180	150	30
0.1	12*10=120	88	32
0.2	12*10=120	92	28
0.3	12*10=120	90	30

Summary

The probabilities of EEG arousals and sleep stage changes were all statistically significantly higher during train vibration of 0.3 mm/s than would be expected from spontaneous reactions alone. No effect of the trains was observed at either 0.1 or 0.2 mm/s compared to the control for any of the physiological parameters examined. Therefore this study did not find that vibration at 0.1 or 0.2 mm/s had an effect on acute reactions, as no reaction was observed at these vibration levels we can also assume that the accompanying low-level noise did not markedly contribute to a physiological response. The effects seen at 0.3 mm/s can therefore be attributed to the vibration exposure, and are not a result of any concurrent train noise.

The results from the pilot study suggests that the physiological reaction threshold during sleep for vibration lies somewhere around 0.3 mm/s. The actual threshold in reality may be slightly higher or slightly lower, since this value of 0.3 mm/s is based on results from only 5 persons, who cannot be considered to fully represent a wider population.

Main study

Exposures

Based on results from the pilot study, the main study used vibration amplitudes of 0.2, 0.3 and 0.4 mm/s. Each amplitude was introduced 12 times during each night, for a total of 36 trains, see Table 7. This is in line with typical nocturnal timetabling in Sweden, where 26 trains can typically occur between 22-06 on the Western mainline between Stockholm and Göteborg, and as many as 69 occur between 22-06 in Sollentuna [16].

Participants

One participant dropped out after the habituation period, and one dropped out after the control night. Data for one participant is missing from Night C. Due to a technical issue, polysomnogram data for one participant is available only from 23:22:30 onwards in Night C.

After excluding the two volunteers who dropped-out, sixteen participants took part in the study (8 males, 8 females, mean age 22 SD ±2.7 years, range 19 – 27 years). Of these, eight participants (50%) rated themselves as being sensitive to noise, and the other 8 were classed as non-noise sensitive. In both the sensitive and non-sensitive subgroups, 4 persons were male and 4 female.

Results

A detailed description of the statistical analyses performed is given in Annex 1 - Statistics.

Event-related cortical reactions

Probabilities were calculated as described in the Methods section. A 60s analysis window from time of event onset was used. . The probabilities for all participants are given in Table 8 and reproduced in Figure 7.

There were significant **main** effects for **awakenings** (p=0.0199) and **sleep stage changes** (p=0.0259). Post-hoc tests revealed that observed response probabilities following **0.4 mm/s were higher than spontaneous probabilities** for both of these reactions (awakening p=0.0177; SSC p=0.0087, multiple testing corrections applied). For SSCs, the difference between baseline and 0.3 mm/s was of marginal significance after applying test corrections (p=0.0606). From Figure 7 it appears that SSC probability increases linearly with vibration amplitude, but this effect has not been examined statistically. Although not statistically significant, from Figure 7 it appears that the **probability of an EEG reaction increases above baseline somewhere in the region of 0.3 mm/s**. This is in line with the findings from the pilot study, which observed effects at 0.3 mm/s but not at 0.2 mm/s.

No significant main effects or interactions of gender or noise sensitivity were found for event-related reaction probabilities. More detailed information is available in Annex 1 - Statistics and Annex 2 – Supplementary figures.

Table 7 Exposure start times and amplitudes in the main study three exposure nights

Event number	*Train*	*Start time*	*Amplitude (mm/s)*		
			Night A	*Night B*	*Night C*
1	1	23:05:00	0.2	0.3	0.4
2	2	23:15:00	0.3	0.4	0.2
3	1	23:28:30	0.3	0.4	0.2
4	2	23:42:00	0.4	0.2	0.3
5	1	23:55:30	0.4	0.2	0.3
6	2	00:09:00	0.2	0.3	0.4
7	2	00:22:30	0.3	0.4	0.2
8	1	00:36:00	0.3	0.4	0.2
9	2	00:49:30	0.4	0.2	0.3
10	1	01:03:00	0.4	0.2	0.3
11	2	01:16:30	0.2	0.3	0.4
12	1	01:30:00	0.2	0.3	0.4
13	1	01:43:30	0.3	0.4	0.2
14	2	01:57:00	0.4	0.2	0.3
15	1	02:10:30	0.4	0.2	0.3
16	2	02:24:00	0.2	0.3	0.4
17	1	02:37:30	0.2	0.3	0.4
18	2	02:51:00	0.3	0.4	0.2
19	2	03:04:30	0.4	0.2	0.3
20	1	03:18:00	0.4	0.2	0.3
21	2	03:31:30	0.2	0.3	0.4
22	1	03:45:00	0.2	0.3	0.4
23	2	03:58:30	0.3	0.4	0.2
24	1	04:12:00	0.3	0.4	0.2
25	1	04:25:30	0.4	0.2	0.3
26	2	04:39:00	0.2	0.3	0.4
27	1	04:52:30	0.2	0.3	0.4
28	2	05:06:00	0.3	0.4	0.2
29	1	05:19:30	0.3	0.4	0.2
30	2	05:33:00	0.4	0.2	0.3
31	2	05:46:30	0.2	0.3	0.4
32	1	06:00:00	0.2	0.3	0.4
33	2	06:13:30	0.3	0.4	0.2
34	1	06:27:00	0.3	0.4	0.2
35	2	06:40:30	0.4	0.2	0.3
36	1	06:54:00	0.4	0.2	0.3

Table 8 Event-related probabilities of observing cortical reactions: EEG arousals (3-15s), awakenings (>15s), combined EEG response (arousals + awakenings) and sleep stage changes (SSC).

Reaction type	*Control*	*0.2 mm/s*	*0.3 mm/s*	*0.4 mm/s*
Arousal	0.12	0.11	0.15	0.13
Awakening	0.02	0.03	0.03	0.06
Arousals + awakenings	0.15	0.15	0.19	0.20
SSC	0.11	0.15	0.17	0.19

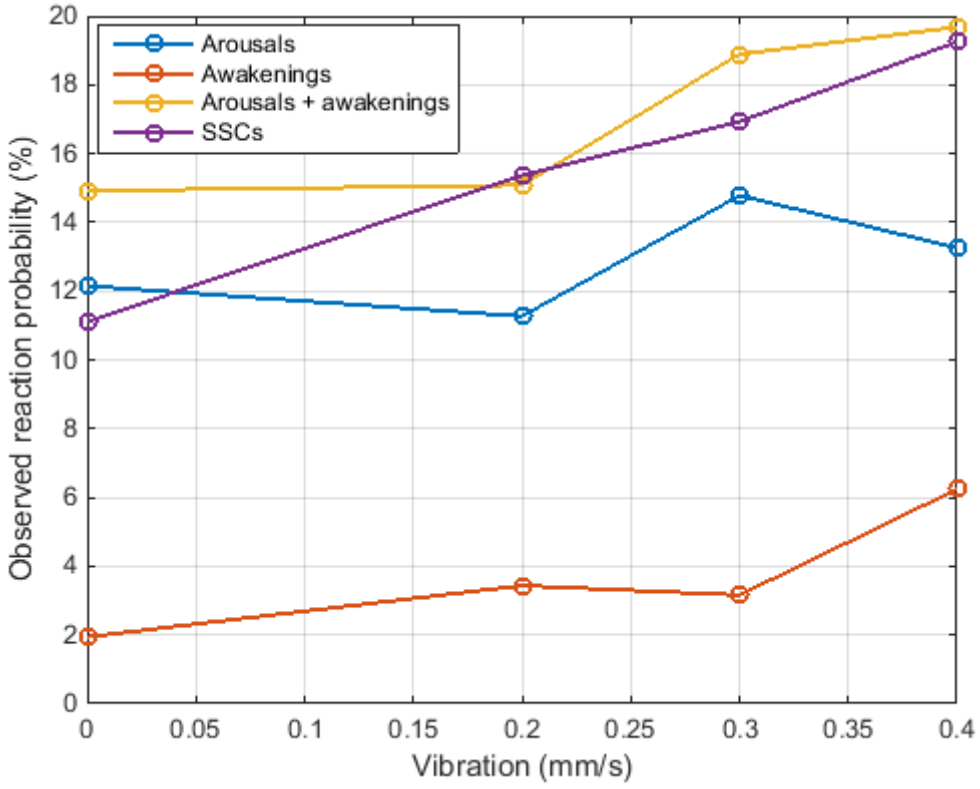

Figure 7 Probability of observing arousals, awakenings, combined EEG reactions and sleep stage changes (SSCs) in the 60s following train onset for different vibration amplitudes. Probabilities for SSCs and awakenings were significantly ($p<0.05$) higher than the spontaneous baseline. Amplitude=0 mm/s is spontaneous probability obtained from the quiet control night.

Heart rate change

The maximum change in heart rate during the 60s analysis window relative to a baseline value calculated from the preceding 10s was calculated for all participants. The results are presented in Figure 8. A main effect of vibration amplitude was found ($p=0.0184$), and post-hoc testing revealed that the change in heart rate was significantly **higher following 0.3 and 0.4 mm/s vibration than the baseline** ($p=0.0157$ and $p=0.0097$ respectively, see Annex I.). Additionally, there was a marginally significant interaction ($p=0.0583$) between vibration amplitude and gender (see Figure 9), meaning that the observed pattern for change in heart rate differs somewhat between men and women.

No significant main effects or interactions of noise sensitivity were found for event-related changes of heart rate. More detailed information is available in Annex 1 - Statistics and Annex 2 – Supplementary figures.

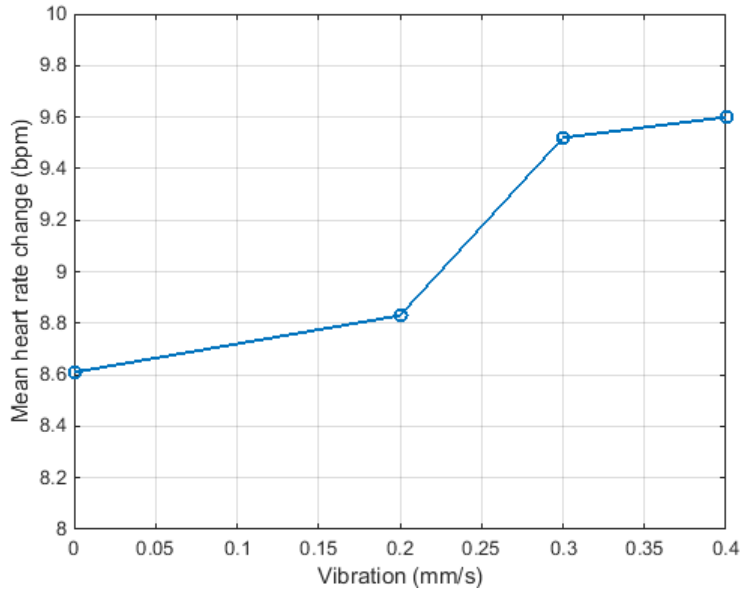

Figure 8 Change in heart rate relative to 10s baseline in the 60s following train onset for different vibration amplitudes. Amplitude=0 mm/s is spontaneous change obtained from the quiet control night.

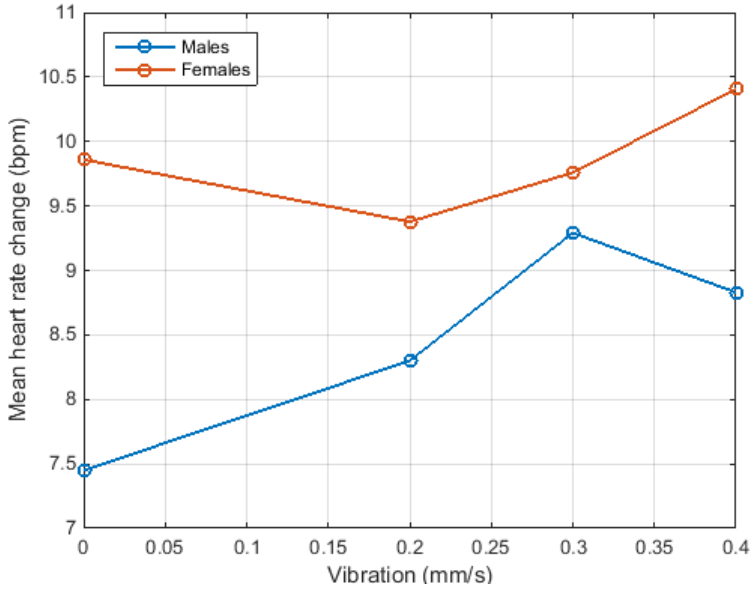

Figure 9 Change in heart rate relative to 10s baseline in the 60s following train onset for different gender groups. Amplitude=0 mm/s is spontaneous change obtained from the quiet control night.

Discussion

Physiological effect thresholds

Although different physiological effects are seen at 0.3 or 0.4 mm/s, the real threshold might be slightly lower, but is not observed because of the resolution of the vibration exposures used. For example, the vibration threshold for awakenings could be around 0.35 mm/s, meaning that effects would be observed at 0.4 mm/s but not at 0.3 mm/s, as in the present study. Similarly, changes in cardiovascular activity might start anywhere between 0.2 and 0.3 mm/s. In practice however, small differences such as these are most likely unimportant, since the true vibration exposure of an individual in their own bed in their own residence will be dependent on a number of factors, including building construction and material, location of bedroom within the building, position of the bed within the room, type of bed and mattress, weight of the sleeping person, and so on.

A summary of the physiological effects during sleep, and the threshold levels for these effects for both noise and vibration are presented in Table 9.

Table 9 Biological effects and thresholds levels for effects during sleep. Noise thresholds are from the WHO Night Noise Guidelines for Europe 2009[1]. Vibration thresholds have been determined in the present work.

Effect	*Threshold, noise[1]*	*Threshold, vibration*
Change in cardiovascular activity	Not determined	0.3 mm/s
EEG awakening	$L_{AFmax,inside}$=35 dB	0.4 mm/s
Changes in sleep structure and fragmentation of sleep	$L_{AFmax,inside}$=35 dB	0.4 mm/s

Statistically significant changes in heart rate were seen at 0.3 and 0.4 mm/s, and awakenings and changes in sleep structure were seen at only 0.4 mm/s. There were also indications, reflected by marginal statistical significance (p=0.05 to 0.1), that changes in sleep structure might be present at 0.3 mm/s.

Train distribution

Thirty six trains during the night, as used in the present work, is in line with realistic railway freight scheduling, and parts of Europe may even have up to 150 trains during the night [22]. In Sweden, typical nocturnal timetabling can involve 26 trains on the Western mainline Stockholm and Göteborg between 22-06, of which 20 (i.e. 77%) can be freight trains [16]. In Sollentuna, there can be as many as 69 trains between 22-06 in Sollentuna. Although EEG reaction probability to nocturnal noise has been shown to decrease as a function of the number of events [23], this has not been found for vibration [8]. The presented probabilities, and subsequent reaction thresholds, are therefore felt to be representative of what might occur in the field nearby to freight lines.

Current guidelines in Sweden

Current Swedish guidelines for vibration state that action must be taken by the local authorities if vibration from newly built, majorly refurbished, and existing railway lines in the bedroom during night-time exceeds 0.7, 1.0 or 2.5 mm/s respectively [9]. Lower limits are in place for when local authorities should at least consider taking action, and are 0.4, 0.4 and 1.0 mm/s for newly built, majorly refurbished, and existing railway lines respectively. The lowest of these limits, 0.4 mm/s for new and refurbished lines, corresponds with the 0.4 mm/s reaction threshold. Taken together with the fact that the degree of heart rate change increases with even higher vibration amplitudes than in the present work [7], and EEG arousal and SSC probabilities increase further with stronger vibration [8], it is very possible that residents living close to freight lines are exposed to vibrations which may illicit physiological response. In the short term, the impact of these acute reactions may be small, but there is currently no information available regarding the long-term effects of chronic vibration exposure. However, sustained exposure to environmental noise can induce sleep effects such as those seen in the present study, and such responses may lead to chronic conditions in the long term, including cardiovascular diseases [24] and metabolic illness [25].

Relation to previous work

The research group has previously investigated the effects of vibration and noise from railway freight traffic on sleep. Much of the work was conducted within the TVANE (Train Vibration And Noise Effects) and CargoVibes projects.

TVANE

A final report of the TVANE project is available in Swedish [16]. Subjective sleep effects determined by questionnaire survey in Kungsbacka at vibrations from 0.1 to 0.5 mm/s are presented in Figure 10. The index is a combination of three questions related to difficulties falling asleep, awakenings during the night and overall sleep quality, where a higher index indicates more disturbed sleep. There is a marked increase in the index above approximately 0.3 mm/s, but it is important to note that the noise level increases close to the railway where the vibration levels are also higher, and the sleep index is affected by both exposures. However, the left diagram in Figure 10 is specifically for sleeping with the window closed and the sleep index is still rather high compared to closed window (right diagram), which indicates that the vibration is important for the sleep quality. For vibrations below 0.3 mm/s there is not much difference between closed and open window conditions

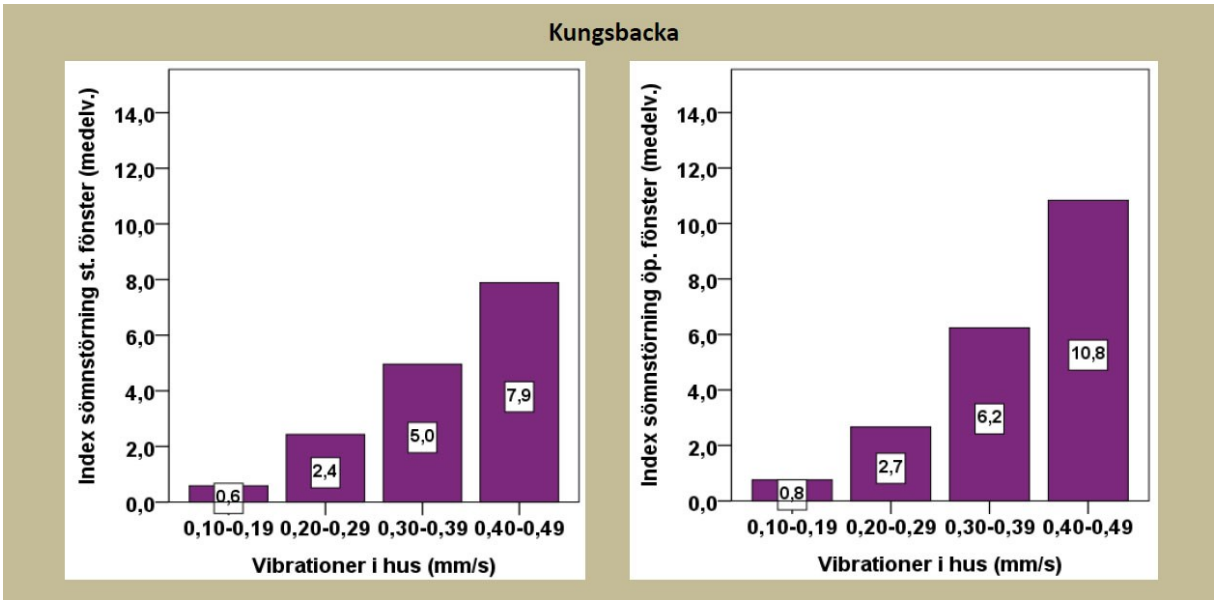

Figure 10 Index (mean) for sleep disturbances (difficulty falling asleep, awakened, poorer sleep quality) with closed (left) and open window (right) in relation to vibration in the house for Kungsbacka area. Reproduced from TVANE final report [16].

CargoVibes

The effects of 0.4 mm/s vibration and noise ($L_{AF,max}$=49.8 dB) on a number of self-reported sleep outcomes are presented in Figure 11 [15]. Poor sleep, difficulty falling asleep and tiredness in the morning due to vibration increased with vibration amplitude. However, differences between nights with noise alone, and noise with 0.4 mm/s vibration (termed "low vibration" in the figure) , were not statistically significant, suggesting that vibration at these levels did not greatly contribute towards subjective sleep outcomes. However, sleep assessments such as these rely on the participant being conscious, in order to rate the effect of an exposure on a specific outcome. The current study presented in this report examined biological reactions where the participant often did not fully awake, namely changes in heart rate, and sleep fragmentation. It is therefore not unexpected that self-reported effects at these threshold levels would be low.

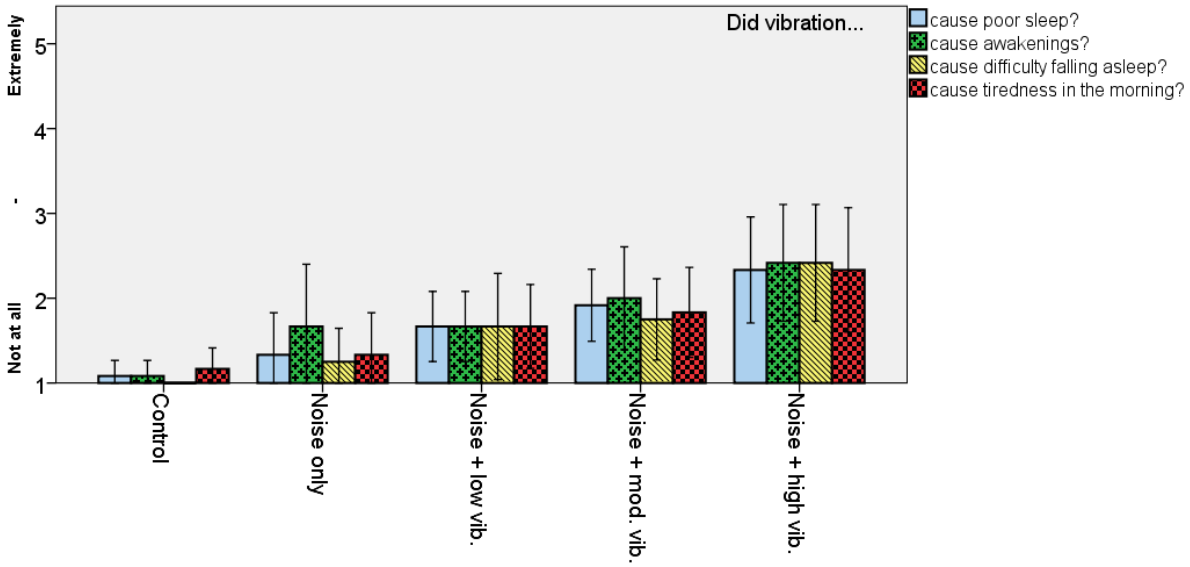

Figure 11 Subjectively rated poor sleep, awakenings, difficulty falling back asleep and tiredness in the mornings. “Low vibration” in this figure equals 0.4 mm/s. ANOVA p=0.018. Adapted from Smith et al. 2013 [15].

Reaction probabilities at 0.7 and 1.4 mm/s were determined in the CargoVibes work, respectively termed “moderate vibration” and “high vibration” in Figure 11 [26]. The observed probability for either an arousal or awakening at 0.7 mm/s was around 30%, and the observed probability for an arousal or awakening at 1.4 mm/s was around 45%. Thus with vibration amplitudes increasing further above the 0.4 mm/s threshold, the likelihood of induced cortical reactions further increases. A similar pattern was seen for sleep stage changes, with the observed probabilities being around 30% and 45% for 0.7 and 1.4 mm/s vibration respectively.

Limitations

The study is limited by the number of participants, meaning that the results should not be overstated. Further work is necessary not only to improve the statistical power, but also to involve a greater diversity of participants. There is no guarantee that reaction thresholds for young, healthy people with good normal sleep would be the same as the thresholds for older persons for instance, whose sleep structures are already different [27]. On the other hand, there are a limited number of studies which provide indications that older subjects may not display as pronounced physiological reactions as younger subjects [3]. Nevertheless, the current findings provide a first indication of where the threshold for the biological effects of vibration may occur.

Conclusion

The two aims were to identify a physiological reaction threshold to vibration, and to examine physiological response at 0.4 mm/s. In summary, changes in sleep stage and awakenings were observed at 0.4 mm/s, while indications were seen at 0.3 mm/s but not 0.2 mm/s. Changes in heart rate were seen at 0.3 and 0.4 mm/s, but not at 0.2 mm/s. This study found that the physiological effects and threshold levels for these WHO defined effects were 0.3 mm/s for changes in cardiac activity, and 0.4 mm/s for EEG awakenings and changes in sleep structure and fragmentation of sleep. In general there were no differences in observed thresholds for men and women. No effects of noise sensitivity were observed for any of the measured outcomes.

Acknowledgement

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Annex 1 - Statistics

Background

It is possible to get confidence intervals for the differences between amplitudes for the event related outcomes. The effect measure is odds ratios. These are not straightforward to interpret, but have been included regardless.

Research questions

Event related outcomes are arousals, awakenings, combined EEG reactions and sleep stage changes. The research questions concerning these event related outcomes are expressed in terms of probabilities.

Do the probabilities in any of the exposure nights differ from the control condition?

Do probabilities differ between the two sensitivity groups, and if so, how?

Do probabilities differ between gender, and if so, how?

We also have one continuous outcome, namely heart rate change. In the following, heart rate change refers to the absolute value of the original variable named heart rate change in the data set. The research questions concerning heart rate change are expressed in terms of mean values.

Do the means of heart rate change in any of the exposure nights differ from the control condition?

Do the means of heart rate change differ between the two sensitive groups, and if so, how?

Do the means of heart rate change differ between gender, and if so, how?

Model

Modelling issues concerning both event related outcomes and heart rate change

We use mixed models to account for dependences between observations within the same individual, i.e. we include individual as a random effect in each model.

In order to answer the different research questions, any model must include the following explanatory variables: amplitude, gender, sensitive (main effects) amplitude*gender, amplitude*sensitive, gender*sensitive (interaction effects). Given the limited amount of data, the three-way interaction term amplitude*gender*sensitive should only be included if necessary. If the p-value of the three-way interaction term is less or equal to 0.05, then the term is retained in the model and otherwise it is dropped. This procedure can be seen as a special case of a backward selection procedure.

All explanatory variables, including amplitude, are entered into the models as factors, as opposed to continuous variables.

We use significance level 0.05 and adjust for multiple comparisons by Dunnett.

Event related specific modelling

There seems to be no great difference between the exposure nights. Therefore we collapse observations over exposure night. (E.g. arousals/possible reactions for id 3 and amplitude 0.2; 3/11, 1/12, 0/11 become 4/34.)

Event related outcomes are not assumed to be normally distributed, but to follow binomial distributions.

Heart rate specific modelling

We evaluate the model fit using log transformation, square root transformation and no transformation of heart rate and choose the one with the best fit.

Results

Modelling issues

The three-way interaction term is removed from every model, even for heart rate change, as opposed to the previous versions. The square root transformation was marginally better than the log transform and therefore we use this transformation for the analysis. Since the square root transformation makes the back-transformed means hard to interpret, I also include a plot of median values for heart rate change.

There were no signs of overdispersion in the models of event related outcomes.

Answers to research questions

For heart rate change there are significant differences between amplitude 0.3 and control, as well as between amplitude 0.4 and control.

For awakenings and sleep stage change there is a significant difference between amplitude 0.4 and control night.

No interactions between amplitude and gender or amplitude and sensitivity had a p-value of <0.05..

The results are presented separately for each outcome below. The first table (for each outcome) gives p-values for F-tests (ProbF) of fixed effects.. For event-related outcomes, the second table (for each outcome) gives estimated probabilities (Mu) and limits of a 95 percent confidence intervals (LowerMu, UpperMu) of the outcome for different amplitudes. These probabilities are computed under a specific statistical model and may differ somewhat to probabilities given by simply dividing the number of events by the number of possible events. For heart rate, the second table gives mean heart rate changes (Mu) and limits of a 95 percent confidence interval (lowermu, uppermu) for different amplitudes. The third table (for each outcome) gives comparisons of the three amplitudes to control, together with both unadjusted p-values (Probt) and Dunnett adjusted p-values (Adjp). For event related outcomes I also

include odds ratios with adjusted 95 percent confidence intervals comparing amplitudes to control.

Arousals

Effect	ProbF
Amplitude	0.4176
gender	0.3234
Amplitude*gender	0.2581
sensitive	0.8936
Amplitude*sensitive	0.3771
gender*sensitive	0.4849

Effect	Amplitude	Mu	LowerMu	UpperMu
Amplitude	0	0.1215	0.08690	0.1673
Amplitude	0.2	0.1127	0.07912	0.1581
Amplitude	0.3	0.1478	0.1071	0.2005
Amplitude	0.4	0.1326	0.09534	0.1815

Effect	Amplitude	_Amplitude	Probt	Adjp	OddsRatio	AdjLowerOR	AdjUpperOR
Amplitude	0.2	0	0.6699	0.9503	0.919	0.567	1.488
Amplitude	0.3	0	0.2320	0.4867	1.255	0.794	1.981
Amplitude	0.4	0	0.5958	0.9109	1.106	0.699	1.750

Awakenings

Effect	ProbF
Amplitude	0.0199
gender	0.0974
Amplitude*gender	0.1481
sensitive	0.4287
Amplitude*sensitive	0.1562
gender*sensitive	0.8749

Effect	Amplitude	Mu	LowerMu	UpperMu
Amplitude	0	0.01946	0.008938	0.04185
Amplitude	0.2	0.03437	0.02031	0.05760
Amplitude	0.3	0.03161	0.01829	0.05408
Amplitude	0.4	0.06240	0.04283	0.09008

Effect	Amplitude	_Amplitude	Probt	Adjp	OddsRatio	AdjLowerOR	AdjUpperOR
Amplitude	0.2	0	0.2175	0.3970	1.794	0.593	5.427
Amplitude	0.3	0	0.2984	0.5202	1.645	0.536	5.046
Amplitude	0.4	0	0.0076	0.0177	3.353	1.209	9.303

Combined EEG reactions

Effect	ProbF
Amplitude	0.1115
gender	0.1361
Amplitude*gender	0.3594
sensitive	0.8014
Amplitude*sensitive	0.8599
gender*sensitive	0.4285

Effect	Amplitude	Mu	LowerMu	UpperMu
Amplitude	0	0.1492	0.1129	0.1946
Amplitude	0.2	0.1508	0.1135	0.1977
Amplitude	0.3	0.1889	0.1461	0.2407
Amplitude	0.4	0.1968	0.1531	0.2492

Effect	Amplitude	_Amplitude	Probt	Adjp	OddsRatio	AdjLowerOR	AdjUpperOR
Amplitude	0.2	0	0.9434	0.9997	1.013	0.655	1.567
Amplitude	0.3	0	0.1044	0.2403	1.328	0.876	2.014
Amplitude	0.4	0	0.0544	0.1324	1.397	0.926	2.107

Sleep stage changes

Effect	ProbF
Amplitude	0.0259
gender	0.9905
Amplitude*gender	0.1988
sensitive	0.7807
Amplitude*sensitive	0.3475
gender*sensitive	0.8337

Effect	Amplitude	Mu	LowerMu	UpperMu
Amplitude	0	0.1111	0.08220	0.1485
Amplitude	0.2	0.1537	0.1174	0.1987
Amplitude	0.3	0.1693	0.1319	0.2146
Amplitude	0.4	0.1925	0.1520	0.2406

Effect	Amplitude	_Amplitude	Probt	Adjp	OddsRatio	AdjLowerOR	AdjUpperOR
Amplitude	0.2	0	0.0898	0.2039	1.453	0.863	2.448
Amplitude	0.3	0	0.0243	0.0606	1.630	0.982	2.706
Amplitude	0.4	0	0.0033	0.0087	1.907	1.157	3.144

Heart rate

Effect	ProbF
Amplitude	0.0184
sensitive	0.6944
Amplitude*sensitive	0.4859
gender	0.5016
Amplitude*gender	0.0583
sensitive*gender	0.7643

Effect	Amplitude	mu	lowermu	uppermu
Amplitude	0	8.61	6.71	10.75
Amplitude	0.2	8.83	6.90	11.00
Amplitude	0.3	9.52	7.52	11.77
Amplitude	0.4	9.60	7.58	11.86

Effect	Amplitude	_Amplitude	Probt	Adjp
Amplitude	0.2	0	0.5541	0.8873
Amplitude	0.3	0	0.0157	0.0425
Amplitude	0.4	0	0.0097	0.0268

Comments

The model fit is not completely satisfactory for the outcome awakenings. The lack of fit reveals itself if one compares the overall estimate for control night with the estimates for control night divided by gender and sensitivity, as revealed by the graph. The lack of fit is due to the fact that there are quite a few observations with zero awakenings. Such data is not completely satisfactorily modelled with the current binomial model. I checked that the result (difference between amplitude 0.4 and control) still hold with a, for the current data, more appropriate model, namely a Poisson model. And it does!

Appendix

The following tables list the values for each subgroup, grouped by both gender and noise sensitivity.

Arousals

Amplitude	sensitive	gender	mu	sensitive_gender
0.0	0	0	0.13892	Non-sensitive Males
0.2	0	0	0.14986	Non-sensitive Males
0.3	0	0	0.22278	Non-sensitive Males
0.4	0	0	0.12400	Non-sensitive Males
0.0	0	1	0.09677	Non-sensitive Females
0.2	0	1	0.06935	Non-sensitive Females
0.3	0	1	0.13258	Non-sensitive Females
0.4	0	1	0.11648	Non-sensitive Females
0.0	1	0	0.12705	Sensitive Males
0.2	1	0	0.15013	Sensitive Males
0.3	1	0	0.13836	Sensitive Males
0.4	1	0	0.12632	Sensitive Males
0.0	1	1	0.12682	Sensitive Females
0.2	1	1	0.10090	Sensitive Females
0.3	1	1	0.11400	Sensitive Females
0.4	1	1	0.16831	Sensitive Females

Awakenings

Amplitude	sensitive	gender	mu	sensitive_gender
0.0	0	0	0.053459	Non-sensitive Males
0.2	0	0	0.037952	Non-sensitive Males
0.3	0	0	0.019382	Non-sensitive Males
0.4	0	0	0.063074	Non-sensitive Males
0.0	0	1	0.007985	Non-sensitive Females
0.2	0	1	0.046520	Non-sensitive Females
0.3	0	1	0.014923	Non-sensitive Females
0.4	0	1	0.051927	Non-sensitive Females
0.0	1	0	0.044729	Sensitive Males
0.2	1	0	0.024246	Sensitive Males
0.3	1	0	0.063040	Sensitive Males
0.4	1	0	0.071820	Sensitive Males
0.0	1	1	0.007237	Sensitive Females
0.2	1	1	0.032480	Sensitive Females
0.3	1	1	0.053328	Sensitive Females
0.4	1	1	0.064347	Sensitive Females

Combined EEG reactions

Amplitude	sensitive	gender	mu	sensitive_gender
0.0	0	0	0.19602	Non-sensitive Males
0.2	0	0	0.19466	Non-sensitive Males
0.3	0	0	0.24773	Non-sensitive Males
0.4	0	0	0.19188	Non-sensitive Males
0.0	0	1	0.10729	Non-sensitive Females
0.2	0	1	0.11323	Non-sensitive Females
0.3	0	1	0.14890	Non-sensitive Females
0.4	0	1	0.16812	Non-sensitive Females
0.0	1	0	0.17549	Sensitive Males
0.2	1	0	0.17049	Sensitive Males
0.3	1	0	0.20500	Sensitive Males
0.4	1	0	0.19806	Sensitive Males
0.0	1	1	0.13167	Sensitive Females
0.2	1	1	0.13563	Sensitive Females
0.3	1	1	0.16527	Sensitive Females
0.4	1	1	0.23302	Sensitive Females

Sleep stage changes

Amplitude	sensitive	gender	mu	sensitive_gender
0.0	0	0	0.12645	Non-sensitive Males
0.2	0	0	0.18332	Non-sensitive Males
0.3	0	0	0.15771	Non-sensitive Males
0.4	0	0	0.13219	Non-sensitive Males
0.0	0	1	0.11034	Non-sensitive Females
0.2	0	1	0.16302	Non-sensitive Females
0.3	0	1	0.14336	Non-sensitive Females
0.4	0	1	0.21097	Non-sensitive Females
0.0	1	0	0.11554	Sensitive Males
0.2	1	0	0.14941	Sensitive Males
0.3	1	0	0.20468	Sensitive Males
0.4	1	0	0.18056	Sensitive Males
0.0	1	1	0.09426	Sensitive Females
0.2	1	1	0.12412	Sensitive Females
0.3	1	1	0.17619	Sensitive Females
0.4	1	1	0.26450	Sensitive Females

Heart rate

Amplitude	sensitive	gender	predicted
0.0	0	0	7.0148
0.2	0	0	7.8852
0.3	0	0	8.6118
0.4	0	0	7.8749
0.0	0	1	9.9391
0.2	0	1	9.5055
0.3	0	1	9.6338
0.4	0	1	9.9490
0.0	1	0	7.8970
0.2	1	0	8.7250
0.3	1	0	9.9966
0.4	1	0	9.8386
0.0	1	1	9.7784
0.2	1	1	9.2516
0.3	1	1	9.8833
0.4	1	1	10.8730

sensitive	gender	Amplitude	VarName	median	sensitive_gender
0	0	0.0	hr_change	6.50	Non-sensitive Males
0	0	0.2	hr_change	7.20	Non-sensitive Males
0	0	0.3	hr_change	8.70	Non-sensitive Males
0	0	0.4	hr_change	7.25	Non-sensitive Males
0	1	0.0	hr_change	9.00	Non-sensitive Females
0	1	0.2	hr_change	8.90	Non-sensitive Females
0	1	0.3	hr_change	9.00	Non-sensitive Females
0	1	0.4	hr_change	9.40	Non-sensitive Females
1	0	0.0	hr_change	6.20	Sensitive Males
1	0	0.2	hr_change	6.95	Sensitive Males
1	0	0.3	hr_change	6.90	Sensitive Males
1	0	0.4	hr_change	8.75	Sensitive Males
1	1	0.0	hr_change	7.70	Sensitive Females
1	1	0.2	hr_change	7.90	Sensitive Females
1	1	0.3	hr_change	9.70	Sensitive Females
1	1	0.4	hr_change	8.70	Sensitive Females

Interactions with gender

In the following tables, gender 0 = male, and gender 1 = female.

Arousals

Effect	Amplitude	gender	Mu
Amplitude*gender	0	0	0.1329
Amplitude*gender	0	1	0.1109
Amplitude*gender	0.2	0	0.1500
Amplitude*gender	0.2	1	0.08379
Amplitude*gender	0.3	0	0.1766
Amplitude*gender	0.3	1	0.1230
Amplitude*gender	0.4	0	0.1252
Amplitude*gender	0.4	1	0.1404

Awakenings

Effect	Amplitude	gender	Mu
Amplitude*gender	0	0	0.04891
Amplitude*gender	0	1	0.007602
Amplitude*gender	0.2	0	0.03036
Amplitude*gender	0.2	1	0.03890
Amplitude*gender	0.3	0	0.03518
Amplitude*gender	0.3	1	0.02838
Amplitude*gender	0.4	0	0.06732
Amplitude*gender	0.4	1	0.05782

Combined EEG reactions

Effect	Amplitude	gender	Mu
Amplitude*gender	0	0	0.1855
Amplitude*gender	0	1	0.1189
Amplitude*gender	0.2	0	0.1823
Amplitude*gender	0.2	1	0.1240
Amplitude*gender	0.3	0	0.2257
Amplitude*gender	0.3	1	0.1569
Amplitude*gender	0.4	0	0.1949
Amplitude*gender	0.4	1	0.1986

Sleep stage changes

Effect	Amplitude	gender	Mu
Amplitude*gender	0	0	0.1209
Amplitude*gender	0	1	0.1020
Amplitude*gender	0.2	0	0.1657
Amplitude*gender	0.2	1	0.1425
Amplitude*gender	0.3	0	0.1800
Amplitude*gender	0.3	1	0.1591
Amplitude*gender	0.4	0	0.1548
Amplitude*gender	0.4	1	0.2367

Heart rate

Effect	Amplitude	gender	mu
Amplitude*gender	0	0	7.4494
Amplitude*gender	0	1	9.8586
Amplitude*gender	0.2	0	8.2997
Amplitude*gender	0.2	1	9.3781
Amplitude*gender	0.3	0	9.2913
Amplitude*gender	0.3	1	9.7582
Amplitude*gender	0.4	0	8.8295
Amplitude*gender	0.4	1	10.4059

Interactions with sensitivity

In the following tables, sensitive 0 = non-noise sensitive, and sensitive 1 = noise sensitive.

Arousals

Effect	Amplitude	sensitive	Mu
Amplitude*sensitive	0	0	0.1162
Amplitude*sensitive	0	1	0.1269
Amplitude*sensitive	0.2	0	0.1028
Amplitude*sensitive	0.2	1	0.1234
Amplitude*sensitive	0.3	0	0.1731
Amplitude*sensitive	0.3	1	0.1257
Amplitude*sensitive	0.4	0	0.1202
Amplitude*sensitive	0.4	1	0.1461

Awakenings

Effect	Amplitude	sensitive	Mu
Amplitude*sensitive	0	0	0.02088
Amplitude*sensitive	0	1	0.01814
Amplitude*sensitive	0.2	0	0.04203
Amplitude*sensitive	0.2	1	0.02807
Amplitude*sensitive	0.3	0	0.01701
Amplitude*sensitive	0.3	1	0.05799
Amplitude*sensitive	0.4	0	0.05725
Amplitude*sensitive	0.4	1	0.06799

Combined EEG reactions

Effect	Amplitude	sensitive	Mu
Amplitude*sensitive	0	0	0.1462
Amplitude*sensitive	0	1	0.1523
Amplitude*sensitive	0.2	0	0.1494
Amplitude*sensitive	0.2	1	0.1522
Amplitude*sensitive	0.3	0	0.1936
Amplitude*sensitive	0.3	1	0.1843
Amplitude*sensitive	0.4	0	0.1797
Amplitude*sensitive	0.4	1	0.2150

Sleep stage changes

Effect	Amplitude	sensitive	Mu
Amplitude*sensitive	0	0	0.1182
Amplitude*sensitive	0	1	0.1044
Amplitude*sensitive	0.2	0	0.1729
Amplitude*sensitive	0.2	1	0.1363
Amplitude*sensitive	0.3	0	0.1504
Amplitude*sensitive	0.3	1	0.1900
Amplitude*sensitive	0.4	0	0.1679
Amplitude*sensitive	0.4	1	0.2197

Heart rate

Effect	Amplitude	sensitive	mu
Amplitude*sensitive	0	0	8.4134
Amplitude*sensitive	0	1	8.8126
Amplitude*sensitive	0.2	0	8.6764
Amplitude*sensitive	0.2	1	8.9863
Amplitude*sensitive	0.3	0	9.1156
Amplitude*sensitive	0.3	1	9.9399
Amplitude*sensitive	0.4	0	8.8817
Amplitude*sensitive	0.4	1	10.3493

Annex 2 – Supplementary figures

The following section provides figures for the physiological outcomes grouped by gender, and by noise sensitivity.

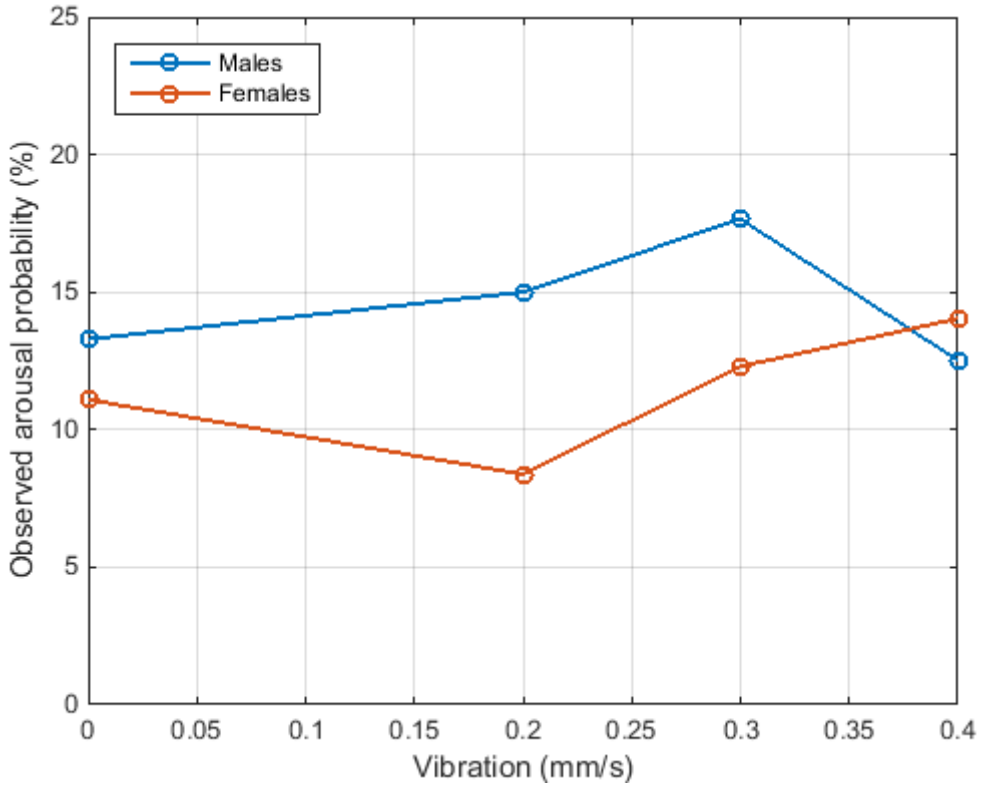

Figure 12 Probability of observing arousals in the 60s following train onset for different vibration amplitudes, grouped by gender. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

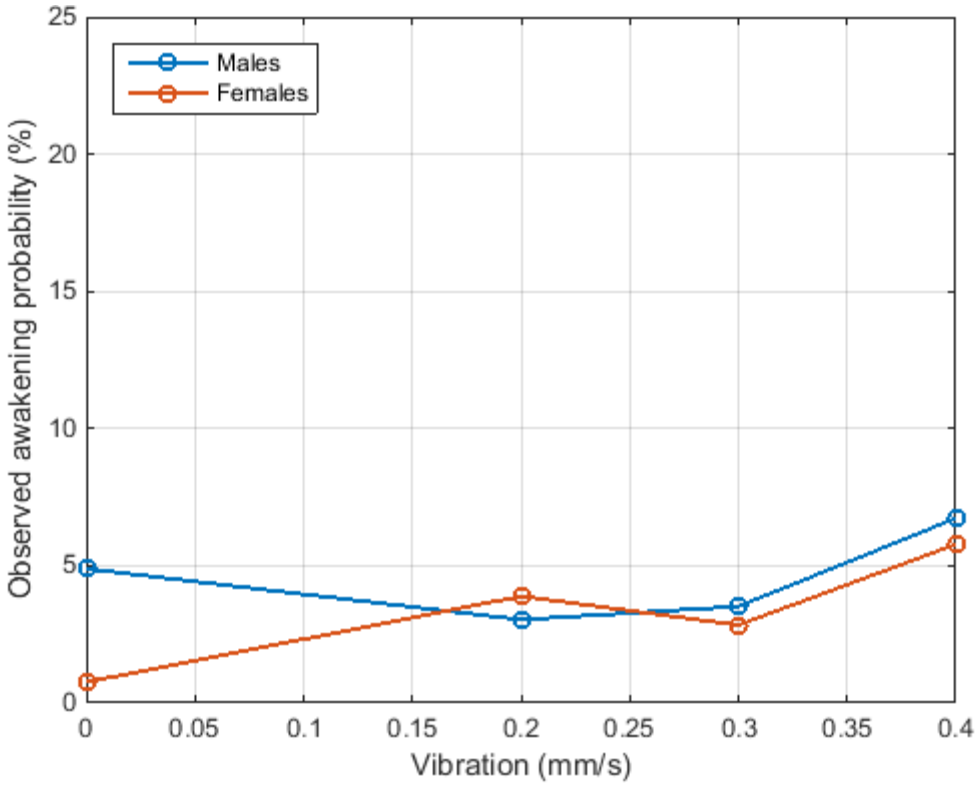

Figure 13 Probability of observing awakenings in the 60s following train onset for different vibration amplitudes, grouped by gender. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

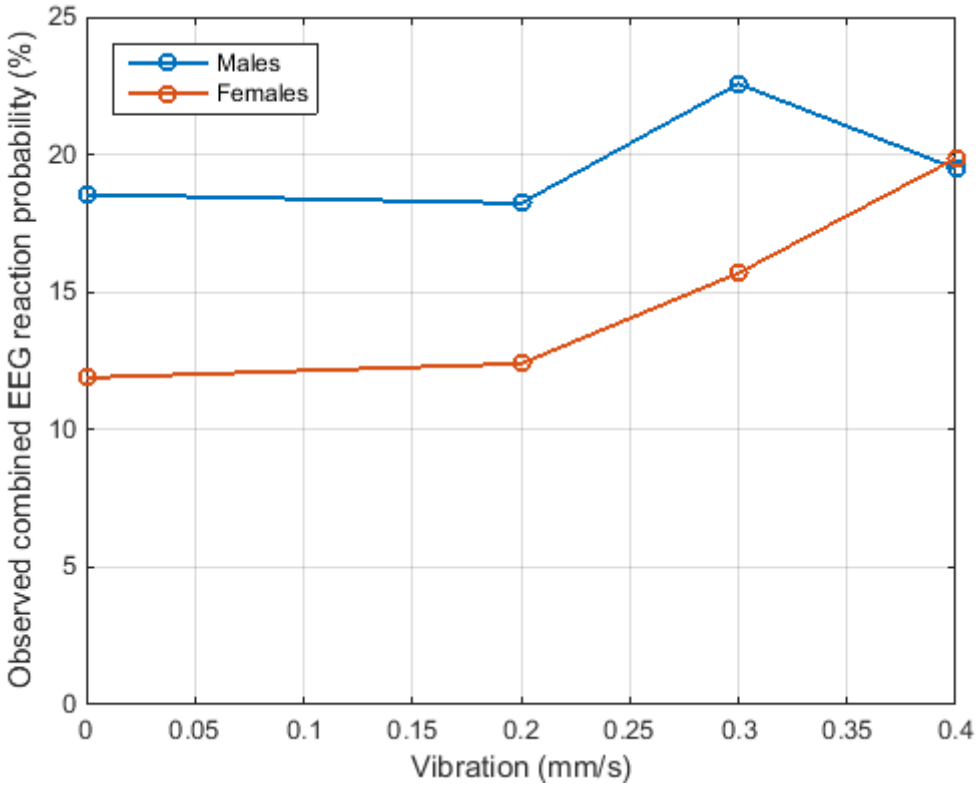

Figure 14 Probability of observing either arousals or awakenings in the 60s following train onset for different vibration amplitudes, grouped by gender. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

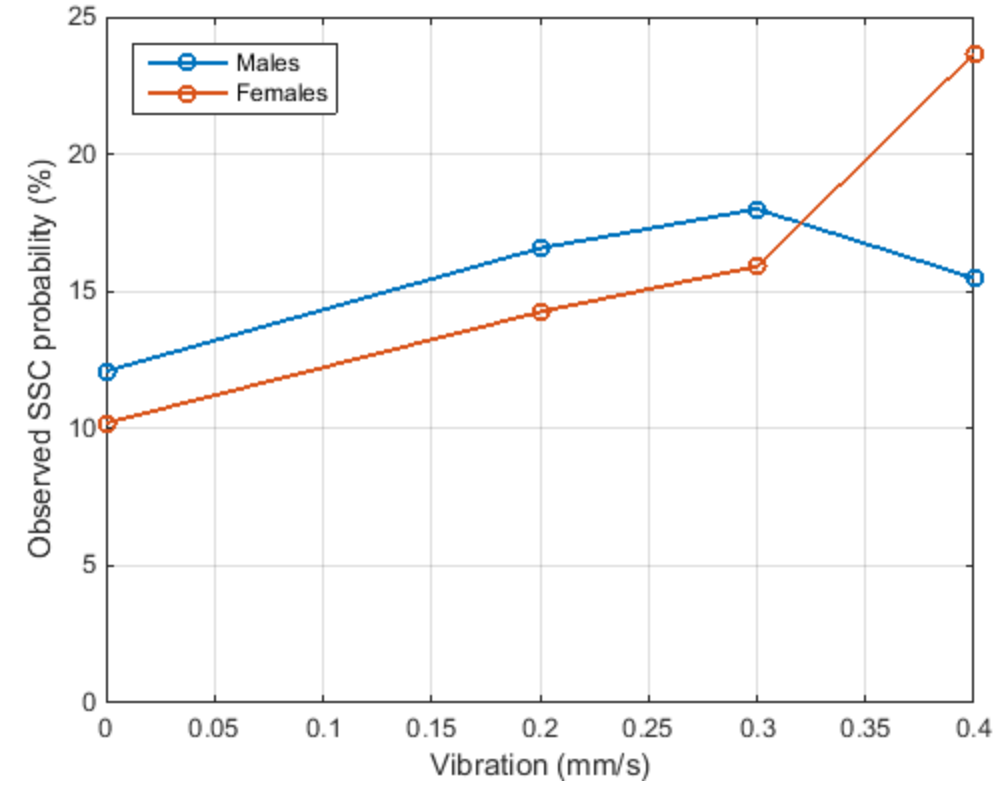

Figure 15 Probability of observing sleep stage changes (SSCs) in the 60s following train onset for different vibration amplitudes, grouped by gender. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

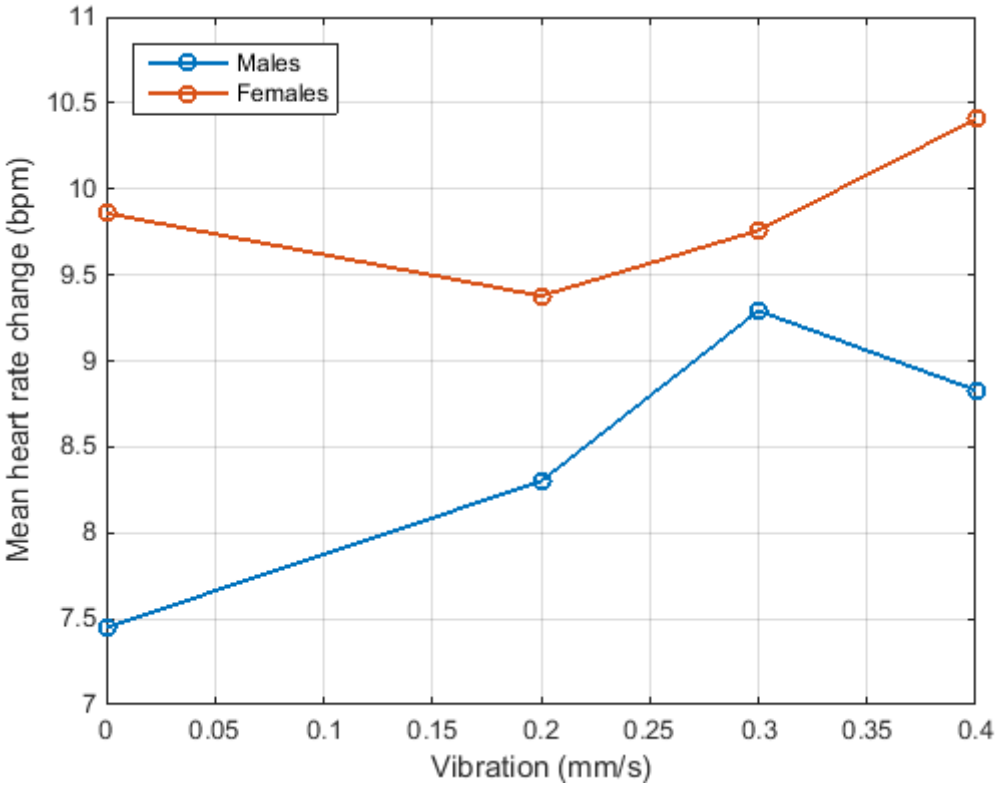

Figure 16 Change in heart rate relative to 10s baseline in the 60s following train onset for different gender groups. Amplitude=0 mm/s is spontaneous change obtained from the control night.

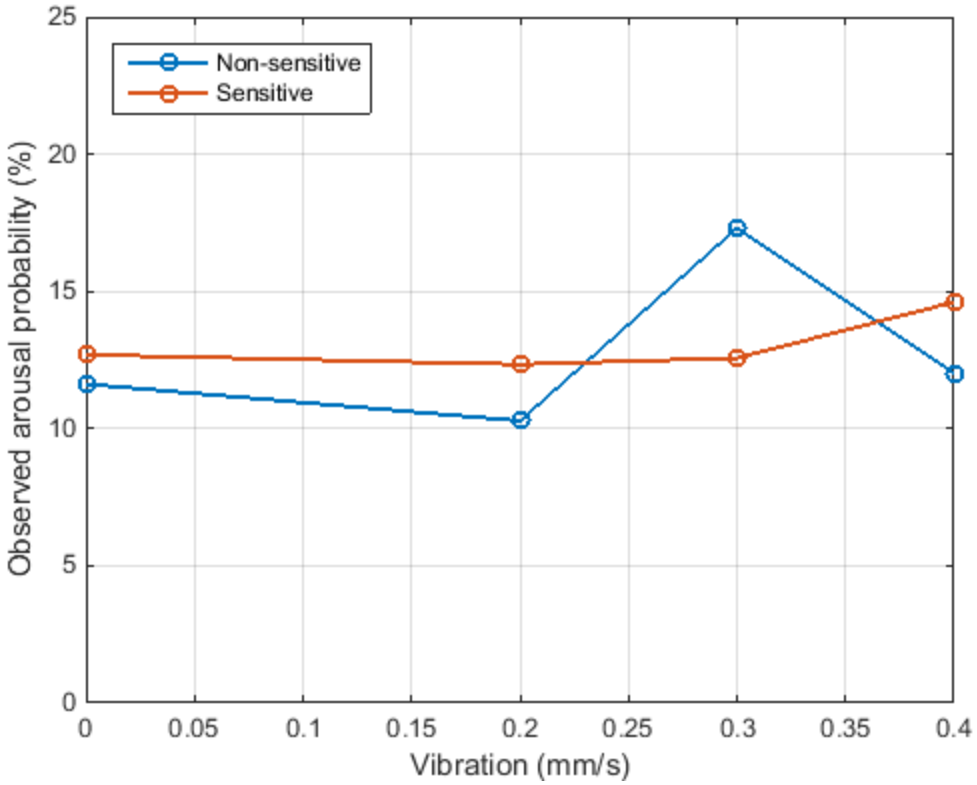

Figure 17 Probability of observing arousals in the 60s following train onset for different vibration amplitudes, grouped by noise sensitivity. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

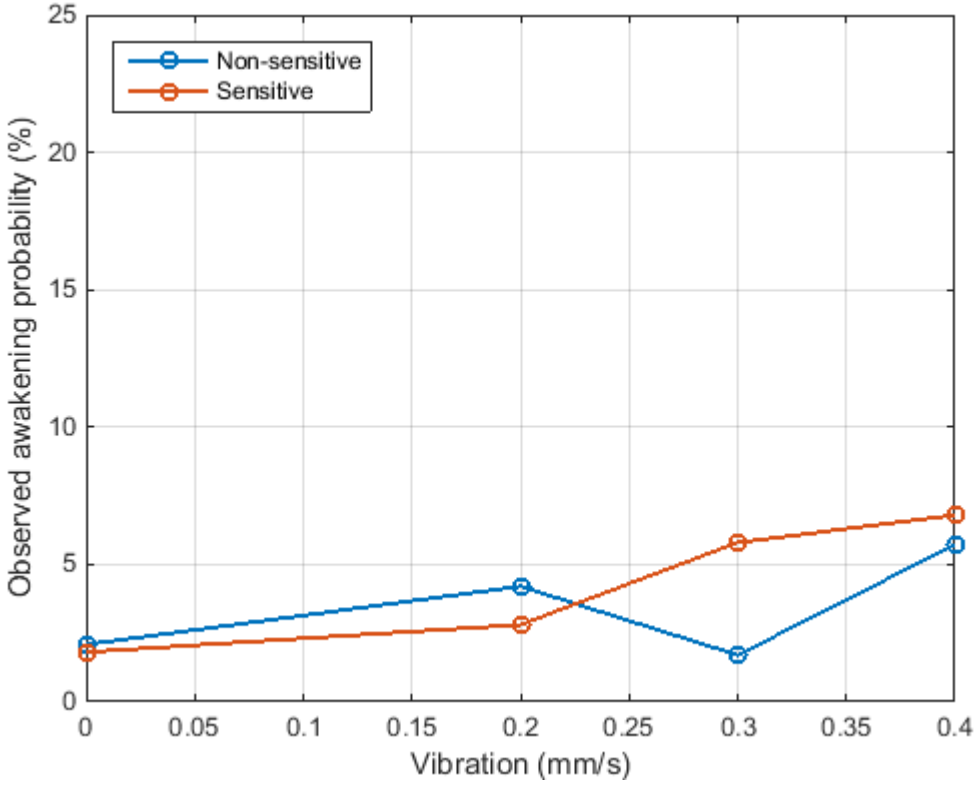

Figure 18 Probability of observing awakenings in the 60s following train onset for different vibration amplitudes, grouped by noise sensitivity. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

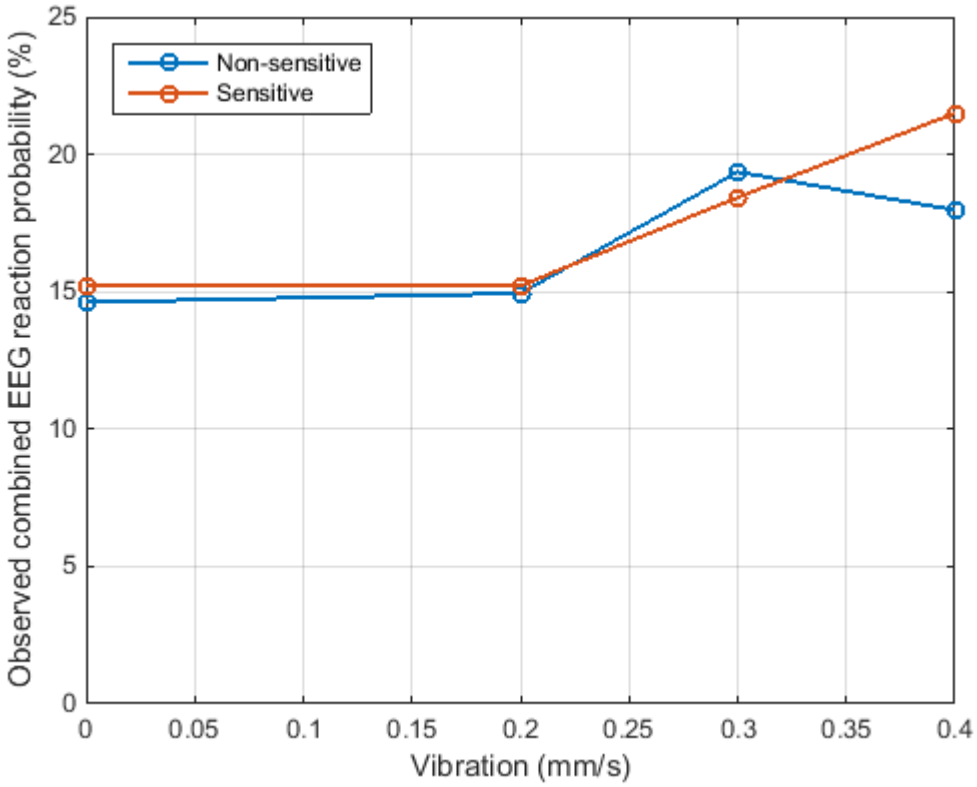

Figure 19 Probability of observing either arousals or awakenings in the 60s following train onset for different vibration amplitudes, grouped by noise sensitivity. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

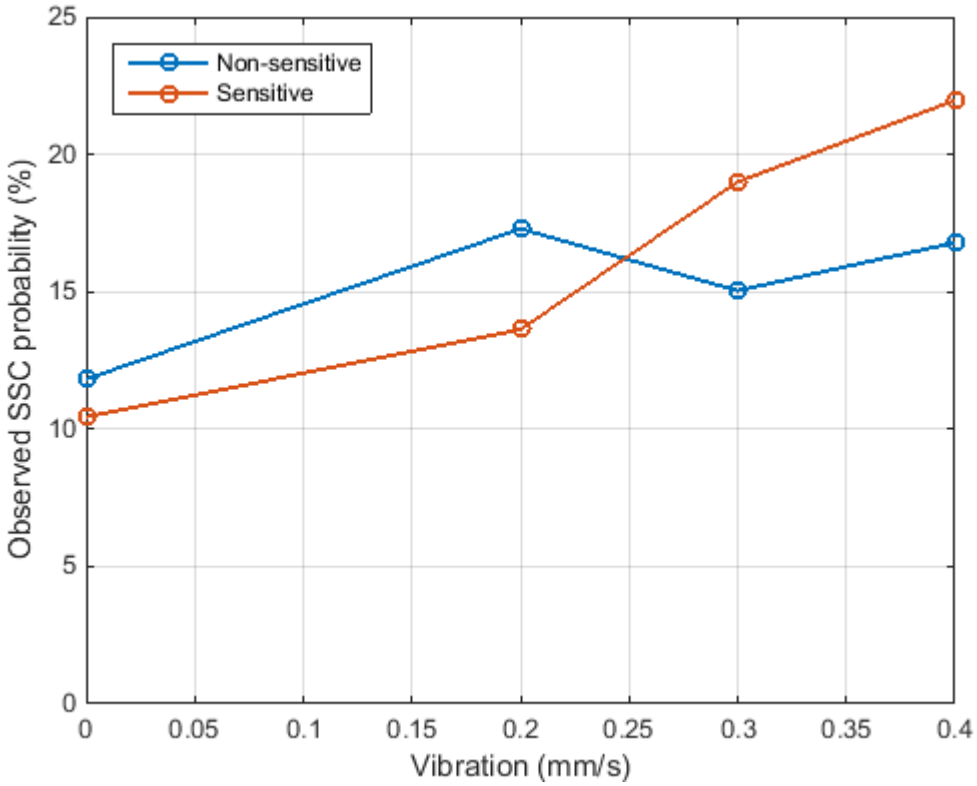

Figure 20 Probability of observing sleep stage changes (SSCs) in the 60s following train onset for different vibration amplitudes, grouped by noise sensitivity. Amplitude=0 mm/s is spontaneous probability obtained from the control night.

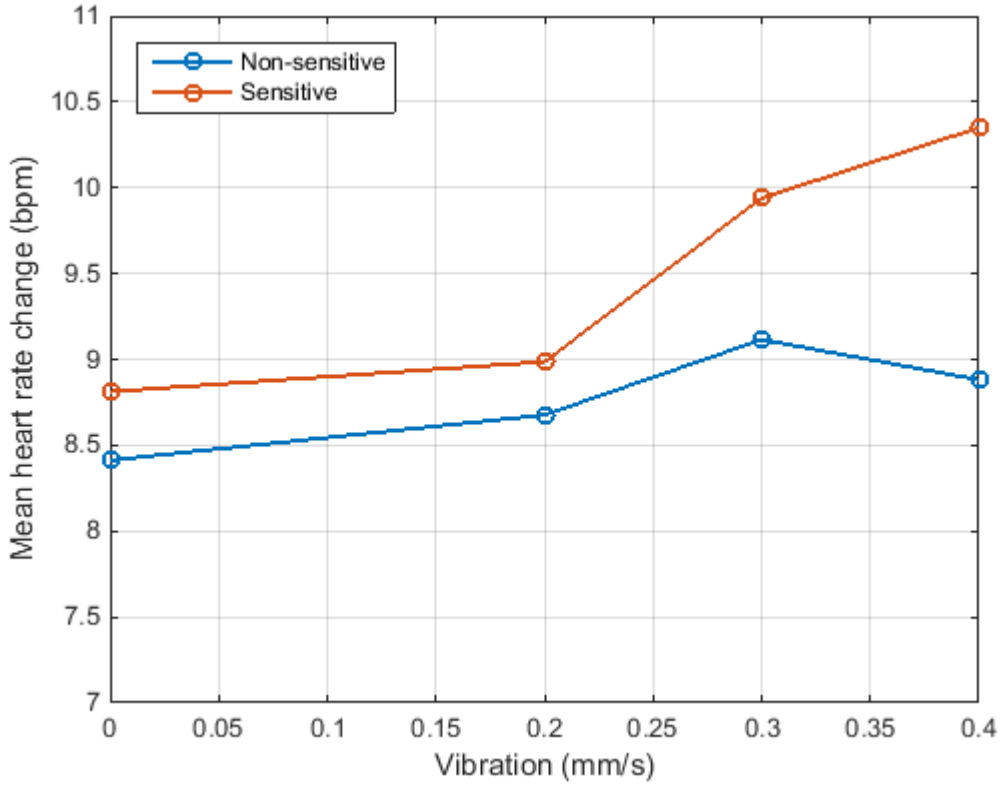

Figure 21 Change in heart rate relative to 10s baseline in the 60s following train onset for different noise sensitivity groups. Amplitude=0 mm/s is spontaneous change obtained from the control night.

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