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Assessing the exposure-response relationship of sleep disturbance and vibration in field and laboratory settings☆

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ABSTRACT

Exposure to nocturnal freight train vibrations may impact sleep, but exposure-response relationships are lacking. The European project CargoVibes evaluated sleep disturbance both in the field and in the laboratory and provides unique data, as measures of response and exposure metrics are comparable. This paper therefore provides data on exposure-response relationships of vibration and sleep disturbance and compares the relationships evaluated in the laboratory and the field. Two field studies (one in Poland and one in the Netherlands) with 233 valid respondents in total, and three laboratory studies in Sweden with a total of 59 subjects over 350 person-nights were performed. The odds ratios (OR) of sleep disturbance were analyzed in relation to nighttime vibration exposure by ordinal logit regression, adjusting for moderating factors common for the studies. Outcome specific fractions were calculated for eleven sleep outcomes and supported comparability between the field and laboratory settings. Vibration exposure was significantly associated with sleep disturbance, OR = 3.51 (95% confidence interval 2.6–4.73) denoting a three and a half times increase in the odds of sleep disturbance with one unit increased 8 h nighttime log10 Root Mean Square vibration. The results suggest no significant difference between field and laboratory settings OR = 1.37 (0.59–3.19). However, odds of sleep disturbance were higher in the Netherlands as compared to Sweden, indicating unexplained differences between study populations or countries, possibly related to cultural and contextual differences and uncertainties in exposure assessments. Future studies should be carefully designed to record explanatory factors in the field and enhance ecological validity in the laboratory. Nevertheless, the presented combined data set provides a first set of exposure response relationships for vibration-induced sleep disturbance, which are useful when considering public health outcomes among exposed populations.

1. Introduction

The globally increasing transportation, the lack of successful remedies for vehicle generated noise and the increasing populations living in urban areas, all add to the increasing number of people being exposed to health threatening noise levels. Day, evening and night weighted (L_{DEN}) noise levels above 55 dB are considered harmful to human health (European Environment Agency, 2014) and about 125 million people and up to 14 million people are exposed to these levels from road traffic noise and railway noise respectively in Europe (European Environment

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Agency, 2014). Moreover, transportation of goods and people with railway is expected to increase as a consequence of the European Commission transport policy outlined in the White Paper on transport (European Commission, 2011).

Adverse health effects associated with exposure to raised transportation noise levels, include poor sleep quality and sleep disturbance (Basner and McGuire, 2018; Jakovljevic et al., 2006; Miedema and Vos, 2007; Öhrström et al., 2006; Perron et al., 2016), insomnia (Halonen et al., 2012), annoyance (Guski et al., 2017; Miedema and Oudshoorn, 2001), cardiovascular outcomes (Basner et al., 2014; Dratva et al., 2012; Foraster et al., 2017; van Kempen et al., 2018; Sørensen et al., 2011a; Sørensen et al., 2011b) and possibly metabolic disease, as indicated in a few studies for road traffic noise (Sørensen et al., 2013) and aircraft noise (Eriksson et al., 2014). Railway noise has generally been found to be less disturbing (Miedema and Vos, 2007), although studies with more intense rail traffic (Lim et al., 2006) and more recent studies (Hong et al., 2010; Lercher et al., 2010) investigating sleep disturbance and sleep medication intake, indicate that railway noise may have equally or more serious health consequences as compared to road traffic noise.

Freight trains are of particular concern for nocturnal exposure as they, due to limited daytime rail access, predominantly occupy night time scheduled slots. Freight compared to passenger trains has further been found to cause greater annoyance response (Sharp et al., 2014), more frequent awakenings (Saremi et al., 2008), stronger autonomic response (Tassi et al., 2010) and greater nocturnal annoyance (Pennig et al., 2012). The reason for this is unclear, but apart from low frequency noise, railway freight also induces vibration. To our knowledge only four previous studies have evaluated the impact on sleep with reference to rail vibration (Klaeboe et al., 2003; Waddington et al., 2014; van Kamp et al., 2015; Öhrström and Ögren, 2009). Öhrström et al. reported on considerably higher sleep disturbance in areas with both high noise level and vibration than in areas with low vibration. Due to design limitations, no exposure-response relationships were derived. Experimental studies however confirmed a greater sleep disturbance at higher as compared to lower vibration levels (Öhrström and Ögren, 2009). Klæboe et al. derived exposure-response relationships for sleep-specific outcomes, with the greatest relationship found for waking up at night (Klaeboe et al., 2003). Waddington et al. conducted a field survey but data did not provide sufficiently detailed information on the severity of sleep disturbance for the derivation of an exposure-response function (Waddington et al., 2014). Van Kamp et al. investigated annoyance and sleep disturbance due to vibration in a large questionnaire survey of 4927 people living within 300 m of a railroad track in the Netherlands. An effect of exposure to vibration on sleep disturbance was reported to exist, although the proceeding did not include exposure-response relationships.

The European project CargoVibes evaluated the impact on sleep due to night time vibration and noise from freight trains. For an overview of the CargoVibes project see (Persson Waye et al., 2014). Three laboratory studies were conducted with in total 59 participants contributing over 350 person-nights investigating the sleep impact of vibration exposure. Vibration was assessed as a root mean square (RMS) average acceleration over the 8 h nighttime period and frequency weighted according to W_d to account for the frequency and directional dependence of human response (International Organization for Standardization, 1997). Exposure-response relationships between vibration exposure and self-reported outcomes were obtained, and furthermore verified by objective polysomnogram measures (Smith et al., 2016). The suitability of exposure-response relationships derived from laboratory investigations for the effects of noise and vibration on sleep can however be questioned. Laboratory studies are by definition performed in environments different from a sleeper's typical sleeping environment, and although such studies allow accurate control of a desired nocturnal exposure, it has been suggested that an explanation for any observed discrepancies may be due to the laboratory environment not being sufficiently “homelike”. However, field studies also have their limitations as pointed out by Öhrström, the levels of indoor noise in field studies are not always known, which is a severe limitation when considering exposure-response relationships in the field (Öhrström, 2000). Modelled noise and vibration measures may also differ substantially from performed measurements as was shown by Licitra and colleagues (Licitra et al., 2016). Furthermore, vibration exposure is dependent on frequency-, environmentally-, structurally- and individual-moderated factors making it problematic to model accurately (Smith, 2017). Hence, it may be anticipated that both types of studies may be needed to derive exposure response functions.

Within the CargoVibes project, two field surveys were carried out in 2012, one in the Netherlands and one in Poland, which obtained data for the derivation of exposure-response relationships. Comparisons between the experimental and field studies were made possible due to the usage of the same questions for response and the usage of the same metrics and weightings for the calculations of response. The study presented here thus offers a unique opportunity to derive exposure-response relationships of vibration exposures and sleep disturbance and compare the data obtained in the laboratory and the field.

This study therefore aims to derive associations between vibration exposure and sleep disturbance as evaluated in a laboratory setting and in the field using the same calculations of vibration exposure and response measures. Comparisons between exposure response relationships in the field and the laboratory were made taking into account possible implications of differences in the study populations with regard to age, sex, noise sensitivity and vibration tolerance.

2. Methods

2.1. Study populations

Inclusion criteria for the laboratory study were hearing acuity ≤20 dB HL, BMI >18.5 and < 25, no self-reported snoring or sleep problems, sleep hours commensurate with the experimental sleep timings, no-reported allergies and/or hypersensitivity to chemical agents and not being caffeine dependent or a tobacco user. Subjects filled in a questionnaire on personal characteristics before taking part. During the experimental week they answered a questionnaire each morning upon wake up on their sleep the previous night and every evening on how they had felt during the day, for details see (Smith et al., 2016). An equal distribution of noise sensitivity and sex was strived for throughout the various exposure conditions. The study was approved by the Ethics Committee of Gothenburg (Dnr 920-11) and performed in accordance with principles of Declaration of Helsinki. The volunteers gave their informed consent and were financially reimbursed for their participation.

The field studies were performed in accordance with the principles of the Declaration of Helsinki, but as the respondents were approached anonymously, via mail sent to an address rather than to specific individuals, no Ethics approval was deemed applicable. Residents living at a distance of up to 200 m from the rail in the areas of Den Bosch, The Netherlands and Radzionków, Poland were included. The distance of 200 m was chosen as previous studies (Klaeboe et al., 2003) indicated a rapid attenuation with distance and vibration levels likely to be very low at further distance. An accompanying letter explained the purpose of the study to evaluate the response to noise and vibration in their living environment. The family member whose birthday came first after the date of the letter, and were 18 years old or older was asked to fill in the questionnaire. Den Bosch residents were asked to return the questionnaire by mail, while the questionnaire was collected in person by an assistant in Radzionków. In addition to questions on annoyance and sleep disturbance, the field questionnaire comprised questions on the dwelling, demographic, health and personal characteristics. Also included were questions on bedroom window direction and whether the respondents slept with their window open during winter and summer. In addition, factors of special concern for railways such as feeling worried about train accidents in the neighborhood, being concerned of damage to the home by vibrations and the perceived necessity of railways were posed.

Table 1 presents data that were collected for all study populations. Vibration tolerance and noise sensitivity were asked for in the laboratory and field questionnaire using direct questions “How tolerant would you say you are to vibration in general” and “How sensitive would you say you are to noise in general” respectively. The questions were answered on a scale from *Not at all* to *Extremely*. Questionnaire items presented with different scales (1–5 semantic and 0–10 numerical) were standardized into 0–100 scales with *Not at all* (0) to *Extremely* (100) endpoints using the method developed by (Miedema and Oudshoorn, 2001).

2.2. Measures of sleep response

A questionnaire was used to assess sleep outcomes in the laboratory and the field. The core questions on sleep were constructed to be comparable between the study populations. In total, eleven questions measured different dimensions of sleep outcomes (Table 2), such as vibration-related sleep disruption (Q1, Q2, Q3, Q4), general sleep quality (Q5) and restorative properties of sleep (Q6-Q11). For sleep disturbance (Q1), the field questionnaire adopted the recommended phrasing and scale for noise annoyance (Fields et al., 2001; International Organization for Standardization, 2003), replacing “noise annoyance” with “sleep disturbance”: “*Thinking of the last* 12 months *or so when at home, which number between 0 and 10 best shows how much your sleep is disturbed by vibration from freight trains?*” Responses were from *Not at all* (0) to *Extremely* (10). Included in the field questionnaire was the addition of *Do not notice* to ascertain whether the vibrations were noticed or not. The question in the laboratory study was phrased “*How disturbed was your sleep by vibrations from trains during the night?*” using the same 11-grade response scale as in the field study. In the field the questions Q2-Q4 were answered with a filter question of sleep disturbance frequency, and if disturbed sometimes or often, the degree of disturbance (*a bit, rather, very*) was answered. This was in accordance with (Öhrström et al., (2006)). In the laboratory version only the degree of disturbance on Q2-Q4 were answered on a 5-grade scale from *Not at all* to *Extremely*. Questions on sleep quality (Q5) and restorative properties of sleep (Q6-Q11) followed the same response pattern for laboratory and field. In the laboratory study, sleep outcomes were also measured objectively with polysomnography, the results of which are reported elsewhere (Croy et al., 2013; Smith et al., 2013; Smith et al. 2016; Smith et al. 2017).

2.3. Facilities, study site and exposures

2.3.1. Laboratory

The sleep laboratory was designed with the focus of providing ecological validity while at the same time enabling accurate exposures and measures of response. The laboratory was built as an apartment with a separate entrance to which the subjects have their own key. The apartment comprises a kitchen/living room, bathroom and toilets as well as three rooms furnished as typical bedrooms with a bed, chairs, desk and small chest of drawers (Fig. 1). The bedrooms were individually isolated from external noise and vibration (for more details www.amm.se/soundenvironment). For the exposures, the low frequencies of the freight train noise (<125 Hz) were emitted via eighty eight 10-inch loudspeakers concealed within the ceiling in each bedroom, while the higher frequencies were reproduced by loudspeaker cabinets in two of the upper corners of each room. Since the background levels in the bedrooms were unnaturally low (<14 dBA), band-pass filtered pink noise simulating ventilation noise was introduced throughout the trial at a level of 25 dBA measured at the pillow. Each noise stimulus was accompanied by vibration (rise time (0 mm/s to first peak = 5.6 s). Vibration was introduced horizontally along the length of the bed using an electrodynamic transducer (EarthquakeSound Q10B, frequency response 5–70 Hz). Noise and vibration exposure was controlled by a fully automated system in a separate control room.

In total eight different exposure conditions were created. Based on analysis of vibration time histories and frequency information of measured freight train pass-bys in northern Europe (Hannelius, 1978; Smith et al., 2012; Ögren and Jerson, 2011), an amplitude modulated 10 Hz vibration signal deemed representative of a typical freight passage was synthesized. Human perception of vibration is frequency- and directionally-dependent, so all vibration levels were therefore frequency weighted according to the direction of the highest amplitude vibration, which in the laboratory was horizontally. As such, the resulting RMS vibration accelerations were W_d weighted according to ISO 2631-1 (International Organization for Standardization, 1997). The vibration signal of a single train was adjusted over different nights to have either a W_d weighted low ($0.0058\ m/s^2$), moderate ($0.0102\ m/s^2$) or high ($0.0204\ m/s^2$) maximum amplitude, measured on the bed frame (1 s time weighting). Noise exposures were audio recordings of freight trains of different durations, rise times and maximum levels, spectrally filtered to correspond to a closed window (for detailed information see (Smith et al., 2013)). Experimental nights consisted

Table 1
Descriptions of the study populations in the laboratory study in Sweden (SE), Den Bosch in the Netherlands (NL) and Radzinoków in Poland (PL).

Participants	Laboratory SE	Field Den Bosch, NL	Field Radzionków, PL
n (response rate)	59 (100%)	130[a] (25.5%)	104 (41.6%)
Sex, % males	47.5%	31.7%	55.8%
Age, mean ± SD (birth year range)	23.1 ± 2.9	49.5 ± 14.3 (1925–1992)	41-50[b] (1925–1990)
[c]Noise sensitivity (0–100), mean ± SD	37.5 ± 12.7	50.1 ± 23.5	37.9 ± 17.2
[c]Vibration tolerance (0–100), mean ± SD	55.1 ± 11.4	63.7 ± 21.9	61.7 ± 14.2

[a] 129 answered the sleep disturbance question.
[b] Median age class.
[c] Higher value for noise sensitivity equals higher sensitivity, higher value for vibration tolerance, equals higher tolerance.

Table 2
Questions evaluated impact on sleep that were comparable between the laboratory and field studies.

Question	Dimension	Item	Comments
Q1	Vibration induced sleep disruption	Sleep disturbance to freight trains	Not at all (0) to Extremely (10); Field included "Do not notice"
Q2		Awakenings	Lab[a]: Response scale Not at all (0) to Extremely (5); Field filtered by frequency and if occurring more often than seldom, answers were reported as "a bit", "rather" or "very"
Q3		Impaired sleep	
Q4		Prevent falling asleep	
Q5	Sleep quality	Describe your sleep quality	Very good (0) to Very bad (10)
Q6	Restorative properties of sleep	Rested - Tired in morning	How do you feel: (0–10) Lab[a] refer to: right now/morning; field refer to: usually/morning
Q7		Relaxed - Tense morning	
Q8		Alert and full of life	How do you feel (0–10)
Q9		Full of energy	Lab[a] refers to daytime period
Q10		Worn out	Field refers to last 12 months
Q11		Tired	

[a] Laboratory.

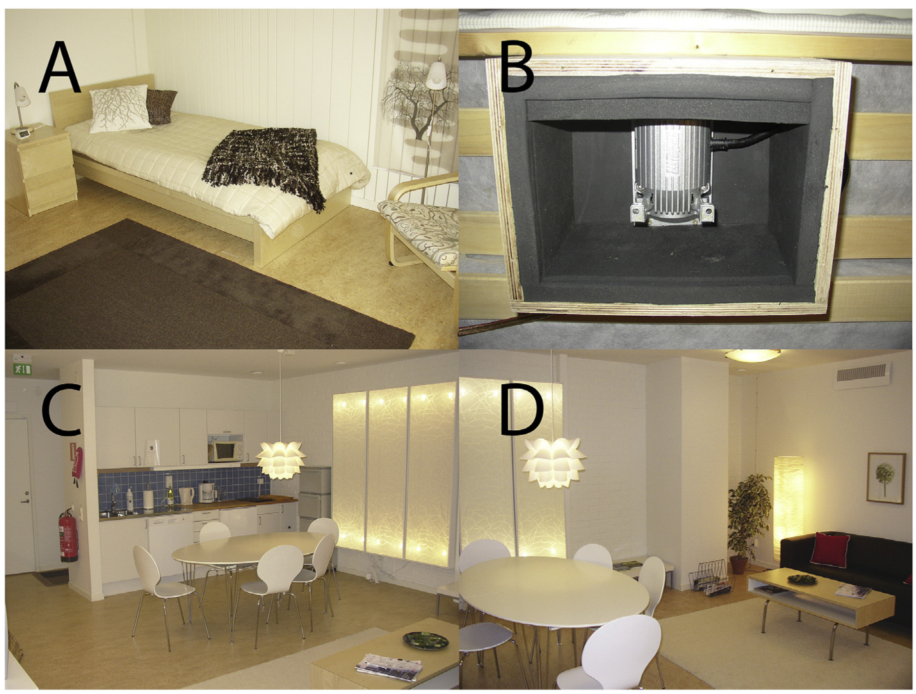

Fig. 1. A: Bedroom. B: Electrodynamic transducer within enclosure (base removed for photograph) C and D: Kitchen and combined dining and living room for the participants.

of 20, 36 or 52 trains. The vibration and noise exposures were chosen to represent commonly occurring levels inside dwellings next to railways with freight trains. The nighttime 8-h vibration data for all exposure conditions used for the exposure-response relationships are given in the Supplementary Material Table S1.

2.3.2. *Field*

The railway line in Den Bosch, a middle sized city in the southern part of the Netherlands, consists of eight tracks in the vicinity of the Central Station. During the daytime, every 2 min a passenger train stops at the station, and during day and evening on average 1.5 freight trains pass by every hour) and during the night about 1 freight train pass by per hour (36 per 24 h).

The railway line in Radzionków, a small industrial town in southern Poland, consists of 3 tracks with primarily freight trains passing by (about 60 per 24 h, of which about 25 are during the night) and electric multiple units serving as passenger trains (24 per 24 h, of which only 2 are during the night). A typical freight train at this location consists of 30 coal wagons.

The procedure for assessing vibration exposure comprised continuous monitoring of vibration in 2–4 reference houses during a period of around a week. In addition, short measurements (30 min in Den Bosch and up to 4 h in Radzionków) were made in 10 and 16 reference houses respectively. In each reference house two accelerometers were installed, one at the foundation on the ground floor and one in the middle of the room. The data acquisition was performed with a sampling frequency of 500 Hz, in combination with an analog Butterworth low–pass filter (cut–off frequency of 100 Hz). Vibration levels in houses other than the reference houses were subsequently estimated by using observed distance relations to estimate the vibration at the foundation, and then applying the amplification factor between foundation and middle of the room of the reference houses to other, similar houses.

Measured vertical and horizontal vibrations were separately weighted according to the weighting curves W_k and W_d in ISO 2631-1 (International Organization for Standardization, 1997). The maximum vibration in the dominant direction was determined, as well as the corresponding RMS value. Based on the measurements and track-use data, the nighttime 8-h RMS acceleration was determined. In Den Bosch, the nighttime RMS acceleration was 0.65 times the 24-h RMS acceleration. In Radzionków, the nighttime RMS acceleration was 0.95 times the 24-h RMS acceleration.

2.4. Study design

2.4.1. Laboratory

Each trial consisted of one habituation night and one control night before four exposure nights that were presented in a Latin square design. In each trial week, three tests subjects were exposed to noise and vibration stimuli during the night from 23.00 to 07.00. Three studies were performed where a combination of vibration amplitudes, number of trains and noise exposures were chosen as described in Table 3. For the exact procedure of the trials, see (Smith et al., 2013; Smith et al. 2016; Smith et al. 2017). In total, 59 participants took part, totaling 350 person-nights, with a sum of 2800 h in bed in the laboratory.

2.4.2. Field study

The response rate of the survey in Den Bosch was 25%, meaning that 130 respondents completed the questionnaire, for 128 of which data on both vibration exposure and sleep disturbance due to vibration from freight trains were available. In Radzionków there were 114 respondents (a response rate of 45%), for 103 of which both vibration exposure and sleep disturbance due to vibration from freight trains were available. The mean 8-h RMS acceleration value per location is given in the Supplementary Material Table S2.

2.5. Data management

We chose self-reported sleep disturbance (Q1) as the main outcome for the derivation of exposure-response relationships, as it is used as a base for calculating Disability Adjusted Life Years lost by noise impacting on sleep (Fritschi et al., 2011). It is also the outcome most often assessed in epidemiological studies and is furthermore the sleep outcome most closely related to the concept of noise annoyance, which *per se* is the most studied outcome of community noise (Fritschi et al., 2011). As the laboratory study evaluated vibration from freight trains only, the comparison between studies was limited to this source. The derivation of exposure-response relationships for sleep disturbance was performed according to the same classification criteria used for annoyance described by (Miedema and Oudshoorn, 2001). The assumption is that the 11-point sleep disturbance scale divides into equally spaced intervals. The 0–10 point scale was hence recalculated into four categories where the value 0 was given to points <28; 1 for ≥ 28 and ≤ 50; 2 for $>50 \leq 72$ and 3 for points >72 The category boundaries are determined by (1) where i is the rank order of the category boundary and m is the number of effective categories. The subsequently rescaled sleep disturbance values based on the midpoints of the categories are given in the Supplementary Material Table S3.

$$scores_{boundary,i} = 100\, {}^{i}\!/_{m} \quad (1)$$

Table 3
Description of the exposure conditions evaluated and the number of participants taking part in the laboratory studies.

Study	Exposures[a]	Number of trains	Number of participants
1	NVl; NVm; NVh; N	36	12
2	NVm; NVH	20, 36	24
3	Vh; NVh; N	36, 52	23
Total	**N, NVl, NVm, NVh, Vh**	**20, 36, 52**	**59**

[a] N = Noise; V=Vibration, l, m and h denote W_d weighted maximum amplitude low (0.0058 m/s^2), moderate (0.0102 m/s^2) and high (0.0204 m/s^2).

2.6. Statistical analysis

Self-reported questionnaire data were combined from all three laboratory studies (Sweden) and together with the two field studies (The Netherlands and Poland) were analyzed in SPSS v.18 (SPSS Inc., Il., USA) and STATA 14.1.

The four categories of the ordinal scale of sleep disturbance (not at all, slightly, moderately, very/extremely disturbed) were analyzed in relation to the base 10 logarithm of the vibration exposures (Log 10 8-h RMS acceleration) to assess the effect of the study condition (field vs laboratory) on the exposure-response relation. Ordinal logit regression analysis was employed (Klaeboe et al., 2003; Waddington et al., 2014), while also accounting for the random-effect caused by the repeated measures in the laboratory studies. Subsequent analyses were performed in crude and multiple regression models to investigate this association in the context of laboratory and field as well as in countries as distinct settings. The likelihood ratio test was sought to examine best-fit models in the multiple regression analysis while controlling for age, sex, vibration tolerance, noise sensitivity and perceived necessity of railways. As the concept of vibration tolerance is less researched we included noise sensitivity as a proxy for vibration in the statistical models. The threshold for statistical significance was set at 95% confidence limits. Confidence intervals not containing 1.0 for odds ratio were considered statistically significant.

Ordinal logit regression analysis is less sensitive to non-linearity and heteroscedasticity of relationships than linear regression and has in recent years gained more recognition in socio-vibrational dose response analyses (Klaeboe et al., 2003; Waddington et al., 2014). In this analysis, we have taken the view that, the odds of the high sleep disturbance category versus the lower categories changes (increases or decreases) with one unit increase in the predictor variable. Based on the satisfied proportional odds assumptions, using the likelihood ratio chi-square test, the same change is assumed between low sleep disturbance category and the combined higher categories. Ordinal logistic regression model using the base 10 logarithm of the vibration exposures was used to analyze associations between the probabilities of persons reporting these different levels of sleep disturbance by vibration as a function of 8 h RMS acceleration. Nights without experimental vibration (control and noise-only conditions) were assumed to have an 8-h weighted RMS acceleration of 0.0001 m/s^2.

In a parallel analysis, the outcome-specific fractions (OSFs) were calculated from the 11 items related to sleep outcomes in both field and laboratory settings (Table 2). As per the mathematical formula (2), individually assigned scores for each sleep outcome were aggregated and divided by the total scores of all eleven outcomes for the corresponding setting forming OSFs. The OSFs ratios for the two settings and their 99% confidence intervals were then calculated for each outcome separately using the Katz adjusted log method (Fagerland et al., 2015).

$$OSF = \frac{\sum (\text{Category}_{n=1}) + \sum (\text{category}_{n=2}) \ldots + \sum (\text{category}_{n=i})}{\sum \text{Category}_{n=i}} \quad (2)$$

The exposure-response curves for the probability of an individual being sleep disturbed (≥ 5) or highly sleep disturbed (≥ 8) in the laboratory were modelled using logistic regression in R 3.1.2, with vibration exposure included as the base 10 logarithm of 8-h weighted RMS acceleration. The exposure-response relationships for the likelihood of an individual reporting sleep disturbance by vibration in the field were calculated in a multilevel grouped regression model in Matlab R2014b (Groothuis-Oudshoorn and Miedema, 2006), assuming a cut-off for disturbance of 50 and 72 on a 100-point scale for "sleep disturbed" and "highly sleep disturbed" respectively.

3. Results

Table 4 gives the OSFs of the eleven sleep outcomes recorded in the laboratory and the combined field studies. The specific fractions between the assessments in the laboratory and the field follow the same pattern. The fractions that were of highest importance, i.e. had the highest OSF value, were sleep disturbance, sleep quality, rested-tired and relaxed-tensed in the morning, which were highest for both the laboratory assessment and the field assessment. The least important OSFs (prevent from falling asleep, waking up, impair sleep quality) also were similar between the study conditions. Further, the differences between the conditions for each fraction were generally very small. Significant differences were found for sleep quality and vibration preventing falling asleep, vibration induced waking up, and vibration impairing sleep that were all assessed to be of relatively higher importance in the laboratory. The restorative properties of sleep, feeling worn out, tired and full of life were assessed to be of relatively higher importance in the field.

The results of the logit ordinal model of sleep disturbance due to vibration from freight trains (Q1) in relation to vibration levels are given in Table 5. Age was initially included in all models and found to be non-significant and therefore not included in the final models. The association between the vibration exposure and sleep disturbance was significant, with a crude odds ratio (OR) of 3.46 (95% confidence interval (CI) 2.57–4.65) and the crude model indicated no significant difference related to the field or laboratory setting (OR = 2.30 (95% CI 0.88–5.98). When adjusting for potential influencing factors common for both settings, such as sex, noise sensitivity and vibration tolerance, the association between vibration and sleep was slightly stronger OR = 3.51 (95% CI 2.60–4.73) and the relationship for the field versus the laboratory setting remained non-significant OR = 1.37 (95% CI 0.59–3.19). Including the location (country) Table 6, in an adjusted regression revealed an overall OR = 3.70 (95% CI 2.74–4.98). The odds of sleep disturbance was higher in the Netherlands with adjusted OR = 4.20 (95% CI 1.62–10.80) as compared to Sweden. For Poland the association was non-significant. For both models, laboratory versus field, respectively country, noise sensitivity significantly increased the odds of sleep disturbance, while vibration tolerance significantly reduced the odds only in the model including country. Sex was non-significant for both models.

In a further analysis of possible contextual or cultural differences related to country for the exposure-response relationships, we studied the associations for the laboratory and the two field studies separately (Table 7).

For the laboratory study (Sweden), the crude model showed that vibration was significantly associated with sleep disturbance (OR = 3.94; 95% CI 2.89–5.36). Adjusting for sex, noise sensitivity, and vibration tolerance did not affect the OR. In the field survey in the Netherlands, the crude model was significantly associated to vibration (OR = 1.90; 95%CI 1.07–3.35), but adjusting for sex, noise sensitivity, vibration tolerance, window opening behavior, concern for property damage, worry and perceived necessity of the rail, reduced the odds ratio just below significance (OR = 1.88; 95% CI 0.95–3.69). For the Polish data, the association between vibration

Table 5
Ordinal logit models for sleep disturbance due to freight vibration by the logarithmic value of RMS[a] as exposure in relation to study settings and country.

Variable	Crude OR[b]	95% CI	Adjusted OR[c]	95% CI
Laboratory vs Field				
Log10 RMS	3.46[d]	2.57, 4.65	3.51[d]	2.60, 4.73
Setting				
Laboratory	Reference	–	Reference	–
Field	2.30	0.88, 5.89	1.37	0.59, 3.19

[a] Root mean square.
[b] Odds Ratio (OR).
[c] OR, adjusted for sex, noise sensitivity and vibration tolerance.
[d] Statistically significant association.

Table 6
Ordinal logit models for sleep disturbance due to freight vibration by the logarithmic value of RMS[a] as exposure in relation to study settings and country.

Variable	Crude OR[b]	95% CI	Adjusted OR[c]	95% CI
Country				
Log10 RMS	3.71[d]	2.76, 4.99	3.70[d]	2.74, 4.98
Sweden	Reference	–	Reference	–
Poland	0.56	0.21, 1.50	0.59	0.24, 1.45
The Netherlands	9.27[d]	3.29, 26.2	4.20[d]	1.62, 10.8

[a] Root mean square.
[b] Odds Ratio (OR).
[c] OR, adjusted for sex, noise sensitivity and vibration tolerance.
[d] Statistically significant association.

Table 4
OSF[a] ratio by type of setting (field vs laboratory) with 99% confidence intervals (CI).

Sub category	OSF[a] field	OSF[a] lab[b]	OSF[a] Ratio (99% CI)	Significant difference[c]
Sleep disturbance	11.2	10.4	1.1 (1.0, 1.2)	0
Prevent from sleep	3.9	5.0	0.8 (0.7, 0.9)	−1
Waking up	4.1	5.8	0.7 (0.6, 0.8)	−1
Impair sleep quality	4.2	5.4	0.8 (0.7, 0.9)	−1
Alert and full of life	9.1	7.9	1.2 (1.0, 1.3)	+1
Full of energy	9.5	8.7	1.1 (1.0, 1.2)	0
Worn out	11.4	8.7	1.3 (1.2, 1.5)	+1
Tired	10.5	9.0	1.2 (1.0, 1.3)	+1
Sleep quality	12.4	15.4	0.8 (0.7, 0.9)	−1
Rested-tired	12.6	13.1	1.0 (0.9, 1.1)	0
Relaxed-tense	11.1	10.6	1.1 (0.9, 1.2)	0
Total	100.0	100.0		

[a] Outcome Specific Fraction.
[b] Laboratory.
[c] Statistically significant difference as indicated by the sign. −1 means the ratio is significantly lower than 1, +1 is significantly higher than 1 and zero means no statistical difference.

Table 7
Ordinal logit model for sleep disturbance due to freight vibration by the logarithmic value of RMS[a] as exposure for the three countries. Only significant covariates were presented.

Variable	Crude OR[b] (95% CI)	Adjusted OR[b] (95% CI)
Model 1: Sweden		
Log10 RMS	3.94* (2.89, 5.36)	3.92[c]* (2.88, 5.34)
Noise sensitive	1.04* (1.01, 1.06)	1.04*(1.00, 1.08)
Model 2: The Netherlands		
Log 10 RMS	1.90* (1.07, 3.35)	1.88[d] (0.95, 3.69)
Noise sensitive	1.03* (1.02, 1.05)	1.03* (1.01, 1.05)
Concerned	1.43* (1.28, 1.61)	1.50* (1.30, 1.73)
Worry	1.25* (1.12, 1.39)	1.20* (1.04, 1.37)
Model 3: Poland		
Log 10 RMS	1.16 (0.67, 1.98)	1.01[d] (0.55, 1.85)
Noise sensitive	1.09* (1.05, 1.12)	1.05* (1.01, 1.10)
Concerned	3.68* (2.38, 5.71)	5.56* (1.32, 23.5)
Necessity	0.75* (0.61, 0.91)	0.75* (0.59, 0.95)

*Statistically significant association.
[a] Root Mean Square.
[b] Odds Ratio (OR).
[c] OR adjusted for sex, noise sensitivity and vibration tolerance.
[d] OR adjusted for sex, noise sensitivity and vibration tolerance, window opening behavior, concern for property damage, worry and perceived necessity of rail.

and sleep disturbance was non-significant. For the Netherlands noise sensitivity, concerned for property damage and worry contributed significantly to the model. In Poland similarly was seen for noise sensitivity, however concerned for property damage greatly increased the odds while perceived necessity reduced the odds for sleep disturbance.

The cumulative proportions of participants having their sleep disturbed and highly disturbed by vibration for the laboratory study and the field studies are presented in Fig. 2. The corresponding formulae for these relationships and the percentage of responses across the different disturbance categories are given in the Supplementary Material. These exposure-response relationships show that the probability of being sleep disturbed and highly sleep disturbed increases with higher 8-hours RMS vibration acceleration exposure, the reported sleep disturbance being highest for the Netherlands study. The graphs also displays that the probability of sleep disturbance in the laboratory study tend to lie in between the field studies or, as for highly disturbed, close to the Polish data.

4. Discussion

Here we presented a dataset consisting of experimental and field data that provides a unique opportunity to evaluate the impact of freight train vibration exposure on sleep in both laboratory and field settings, and to provide a first basis for an exposure-response relationship. The main finding is that vibration exposure was significantly associated with self-reported sleep disturbance and that no significant difference between laboratory and field was found in the combined model. The common field and laboratory adjusted odds of sleep disturbance increased by 3.5 with one unit increase in the 8 h nighttime log10 RMS acceleration for the vibration exposure. Notably, this finding was robust as the odds ratios from the crude model were only slightly changed in the adjusted models after taking into account sex, noise sensitivity and vibration tolerance.

The OSF analysis has undeniably reinforced the study findings by demonstrating a comparable pattern of the most prominent outcomes across the field and the laboratory data. From a survey study point of view, transforming individual-level records into fractions of specific outcomes of interest and 100% representative for a defined study population allows direct quantification, standardization and comparison of outcomes across different countries or regions which is useful for population health applications. Although it may be presented by different terms and abbreviations in the literature, this approach has growing recognitions in medical and public health research (He et al., 2017; Murray et al., 2007). Failing to reach significant differences of most prominent outcomes between the field and laboratory can successfully minimize the associated risk of misinterpreting the main study findings in relation to other important outcomes in this population. Current findings from the OSF analysis can further verify our preference for choosing sleep disturbance as the study outcome, which ranks amongst highest fractions in this study population.

Previous studies on the comparability between field and laboratory derived data on noise-induced sleep are not unambiguous. A

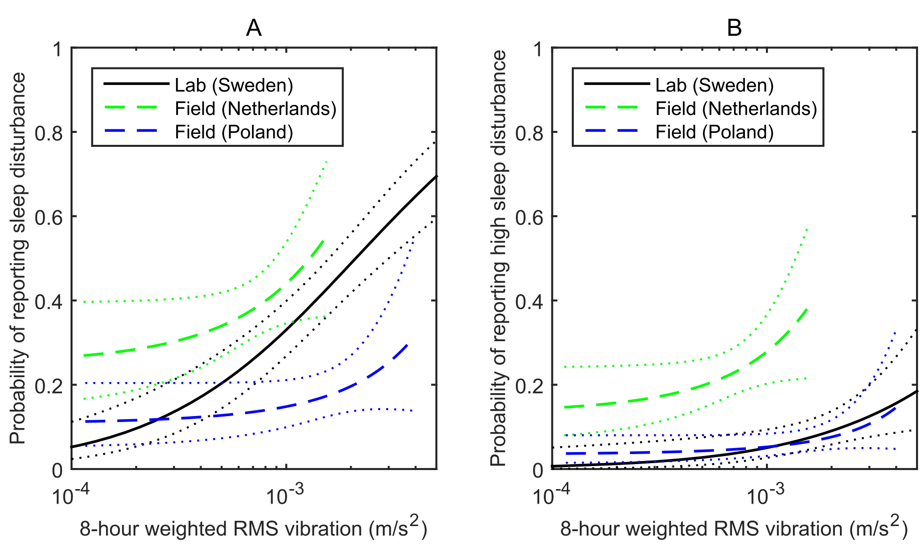

Fig. 2. Cumulative percentage of participants being disturbed (A) or highly disturbed (B) by vibration in the laboratory study (black) and field studies, the Netherlands (green) and Poland (blue). Dotted lines indicate 95% confidence intervals. Vibration, given as an 8-h RMS acceleration, was weighted according to the direction of the highest amplitude, in the laboratory W_d, and in the field W_d or W_k. 2A is adapted from Smith (2017) with permission. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

comprehensive study performed among 128 subjects in the laboratory and compared to 64 residents being exposed to aircraft noise in their homes found that exposure-response curves of field data and laboratory data followed a similar trend, although the annoyance curve was higher for the laboratory study (Quehl and Basner, 2006). It cannot be excluded that individual factors played a role although the authors adjusted for pre-annoyance to aircraft noise and attitudinal factors as well as age. Portier et al. found that total sleep time measured by polysomnography (PSG) was 29 min shorter in the laboratory than in the field, also corroborated by differences in self-reported sleep time (Portier et al., 2000). Sleep architecture (Stage 1–2, Stage 3–4, and rapid eye movement (REM) sleep) was however not significantly different between the laboratory and field environments, and no differences in other self-reported sleep outcomes or number of awakenings were found, indicating no other measurable effect. Finally a study evaluating differential effects of noise on sleep between laboratory and home environments found no differences, either in wrist actigraphy or self-reported sleep outcomes (Skånberg, 2004). The environmental conditions, being in a laboratory-like environment or a home-like environment is probably of large relevance for any comparison. Therefore, it is possible that the great effort spent providing a home-like context was able to reduce a previously reported difference between field- and laboratory-derived data. It has been claimed that the lower values of self-reported and objectively measured outcomes in the field usually found could also be explained by habituation to noise that would occur after years of exposure in your home. While some habituation to noise may be plausible, much less is known of the habituation process to vibration. It could be hypothesized that attention during sleep to vibrations from naturally occurring sources such as volcano eruptions and earthquakes would be vital for survival. From an evolutionary point of view it is hence plausible that vibrations may be less prone to habituation than for example would be the case for some noise sources.

To further match the sleep quality in the laboratory to normal sleep data, we compared the PSG measured sleep during the control night with normal values of sleep data for subjects of the same age range (Bonnet and Arand, 2007), and found further support for the laboratory having little influence. The mean arousal probability (11.4 SD $\pm$ 0.62), awakening probability (2.73 SD $\pm$ 0.39) and combined cortical response probability (17.5 SD $\pm$ 0.33) were all rather similar or lower as compared to normative values (18.6, 5.2 and 23.8 respectively), indicating, that our subjects slept rather well. Naturally, differences in the time frame of the sleep disturbance question could be of importance. In the field, sleep disturbance over the past 12 months was asked while in the laboratory only the previous night was asked for. Further studies would however be advised, including the comparison of sleep assessed in the laboratory setting and in the field among the same individuals.

Our data also indicated important differences related to country or study populations, with the highest odds ratio for the Netherlands data and no significant associations in the Polish data, even though the latter were exposed to higher vibration amplitudes. Possible reasons could be that the Polish population would feel a higher dependency on the railway as the freight of goods came from a mine being the main source of employment in the area. Accordingly, the Polish population considered the freight trains as necessary to a significantly higher degree as compared to the Netherlands population (mean value 8.3 vs 6.7 data not shown) and the odds of being disturbed during sleep was accordingly significantly decreased by 25% when freight was declared necessary by the respondents. Support for this hypothesis was also provided by (Quehl and Basner, 2006) where perceived necessity of air traffic reduced the risk of annoyance for nocturnal aircraft noise for the laboratory study, although this was not verified in the field study.

Worry about accidents was on the contrary significantly adding to the risk of sleep disturbance for the Netherlands population only, possibly explaining some of the higher sleep disturbance reported there. Worry about accidents has previously been indicated to increase the annoyance for train noise (Fields, 1993; Miedema and Vos, 1999) and although much less is known for sleep response and freight vibration, it is possible that being worried about accidents would increase awareness and subsequently reported sleep disturbance to vibration. In accordance with a recent paper (van Kamp et al., 2017), being concerned about property damage increased the odds for being sleep disturbed for both countries, albeit it had a considerably higher impact within the Polish population. Interestingly, for all study populations noise sensitivity but not vibration tolerance significantly increased the odds for sleep disturbance. It is well established that noise sensitivity is as a moderating factor for noise annoyance (van Kamp et al., 2004), but it is less well known how to capture individual susceptibility to vibration exposure. From the present study, it seems as if the wording vibration tolerance captures vibration susceptibility less well as compared to noise sensitivity. Given the current view of noise sensitivity being a state and personality trait (Stansfeld et al., 2017) and seen as a proxy for environmental sensitivity (Palmquist et al., 2014) it may not be surprising that noise sensitivity could perform well as a measure also for susceptibility to vibration.

The exposure-response functions derived for the three countries appeared to be rather similar, with the highest similarity for the laboratory and the Polish data. This was especially the case for highly sleep disturbed. The reason for this is not clear but it is possible that moderating variables would have less influence for the stronger disturbance of sleep as compared to moderate sleep disturbance. This observation has to our knowledge not been properly explored before and should be further elaborated using a larger population sample. Sleep disturbance in the Netherlands population was though consistently higher, also at the lowest vibration levels. When such differences at baseline between groups appear, it is advantageous to use the regression method as it is a robust approach that is able to adjust for potential differences and provide useful interpretations. Although the statistical analyses did not in principal hinder us from deriving one common exposure-response curve, the contextual and cultural differences observed between countries made us choose to derive three country-specific exposure-response functions. Further data from an ongoing large epidemiological study will provide more comprehensive input for a common exposure-response function.

The study limitations are mainly the small study samples and the differences in age, previous vibration exposure and contextual factors between the populations. Sleep patterns change with increasing age, generally resulting in a lighter sleep and more fragmented sleep (Ohayon et al., 2004). For the comparison of laboratory and field this would mean that the field population would be at higher risk of having their sleep disturbed as compared to the younger population in the laboratory, hence reporting higher sleep disturbance. In this study, however the effect was small as age did not significantly impact on the model. Future studies need to closely monitor variables such as concern of property damage, worry about accidents and perceived necessity of freight transportation on rail that may influence the relationships between exposure and response, bearing in mind that the importance may differ between countries and settings. Another limitation was that we were not able to study possible interactions by noise and vibration for sleep disturbance. The study design with equal noise levels between the laboratory exposure nights did not allow for such analyses. Most previous studies of noise and vibration have found that vibration and noise generally enhance annoyance, less is known with regard to sleep disturbance and there is currently no agreement on how to handle the interaction (Trollé et al., 2015). Further studies are here needed. The strength of this study is its certainty and comparability of vibration exposure measurements and sleep response. Given the uncertainties in modelling the vibration exposures from source to residents, laboratory studies as a complement to field studies are greatly needed, which must be designed and carried out to minimize any influence of the laboratory setting itself.

5. Conclusion

The similarities in exposure and outcome assessments of three data sets derived from laboratory and field studies gave us a unique opportunity to provide a first set of exposure response relationships between sleep disturbance and vibration. Important differences between data sets were also identified that needs to be further examined. Our findings require confirmation but are worthy of further exploration, given the increased freight rail transportation and the potential implications of sleep disturbance for short- and long-term health.

Competing financial interests declaration

The authors declare they have no actual or potential competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2018.09.082.

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