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Traffic noise, noise annoyance and psychotropic medication use

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ABSTRACT

Background: Road-traffic noise can induce stress, which may contribute to mental health disorders. Mental health problems have not received much attention in noise research. People perceive noise differently, which may affect the extent to which noise contributes to poor mental health at the individual level. This paper aims to assess the relationships between outdoor traffic noise and noise annoyance and the use of psychotropic medication.

Methods: We conducted a survey to assess noise annoyance and psychotropic medication among residents of the Helsinki Capital Region of Finland. We also assessed the associations of annoyance and road-traffic noise with sleep disorders, anxiety and depression. Respondents were randomly sampled from the Finnish Population registry, and data was collected using a self-administered questionnaire. Outdoor traffic noise was modelled using the Nordic prediction model. Associations between annoyance and modelled façade-noise levels with mental health outcome indicators were assessed using a binary logistic regression while controlling for socio-economic, lifestyle and exposure-related factors.

Results: A total of 7321 respondents returned completed questionnaires. Among the study respondents, 15%, 7% and 7% used sleep medication, anxiolytic and antidepressant medications, respectively, in the year preceding the study. Noise annoyance was associated with anxiolytic drug use, OR = 1.41 (95% CI: 1.02–1.95), but not with sedative or antidepressant use. There was suggestive association between modelled noise at levels higher than 60 dB and anxiolytic or antidepressant use. In respondents whose bedroom windows faced the street, modelled noise was definitively associated with antidepressant use. Noise sensitivity did not modify the effect of noise but was associated with an increased use of psychotropic medication.

Conclusion: We observed suggestive associations between high levels of road-traffic noise and psychotropic medication use. Noise sensitivity was associated with psychotropic medication use.

1. Background

Effective urban planning aims to increase connectivity between people and their routine daily destinations, with the consequence that city dwellers often live closer to roads and motorised traffic. With higher population density, denser road networks and higher volumes of traffic, road traffic becomes an intrusive presence that city dwellers contend with daily. Recent estimates indicate that > 120 million people are exposed to road-traffic noise exceeding 55 dB L_{den} in the European Union, and 90 million of these people reside in urban areas (EEA, 2014). Residential exposure is particularly important because people spend more time at home than elsewhere and commonly attribute a sense of control, predictability and safety to the familiar setting of their residential dwelling (Easthope, 2004). Noise from a constant source such as road traffic may become an invasive fixture in this perceived ‘sanctuary’ leading to an exaggerated sense of helplessness and despair in the more susceptible (Babisch, 2003; Westman and Walters, 1981).

Preceding research on non-auditory endpoints of noise exposure has focused extensively on cardiovascular risks (Babisch, 2003; Bilenko et al., 2015; Foraster et al., 2014; Floud et al., 2013; Gan et al., 2012; Huang et al., 2013; Seidler et al., 2016; Floud et al., 2011). Fewer studies have considered metabolic outcomes, specifically, diabetes mellitus and obesity (Dzhambov and Dimitrova, 2016; Sørensen et al., 2013; Oftedal et al., 2015). Noise annoyance is a negative psychological reaction to noise that has also been broadly investigated (Dratva et al., 2010; Ouis, 2001; Guski et al., 1999; Brown et al., 2015). It expresses

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the sense of disturbance or helplessness due to noise (Guski et al., 1999). There have been suggestions that annoyance, which is sustained over significant periods, can act as an intermediary between noise exposure and the emergence of disease (Hammersen et al., 2016; Niemann and Maschke, 2004; Öhrström, 2004).

Sleep disturbance is a well-known consequence of noise, which is more prevalent with night-time exposures. Sleep disturbance has been demonstrated in both laboratory (Öhrström et al., 1990) and population-based noise studies (Frei et al., 2014). Interventions, which have led to reduced road-traffic noise at residential buildings, have also resulted in reduced sleep disturbance (Öhrström et al., 1990; Amundsen et al., 2013). Higher risks of insomnia, reduced sleep quality and non-restorative sleep have been observed with night-time noises. (Frei et al., 2014; Muzet, 2007; de Kluizenaar et al., 2009; Evandt et al., 2017; Halonen et al., 2012) A meta-analysis of 28 datasets showed that road-traffic noise posed a higher risk of sleep disturbance than rail-traffic noise (Miedema and Vos, 2007). However, this study adjusted for only age as a covariate. For optimal sleep value, the WHO recommends an outside night-time noise limit of 40 dB $L_{night,outside}$ and an interim target of 55 dB $L_{night,outside}$ (World Health Organization, 2009).

Noise sensitivity is an individual innate trait that increases the individual's susceptibility to irritation from noise (Basner et al., 2013; Heinonen-Guzejev et al., 2012; Ryu and Jeon, 2011; van Kamp et al., 2004). It is a consistent determinant of noise annoyance (Miedema and Noise Sensitivity, 2003). Noise-sensitive persons are generally less tolerant of noise and are prone to rate noise as being louder than non-sensitive persons would (Moreira and Bryan, 1972).

Studies that explore chronic neuropsychological sequelae of road-traffic noise are scant. Although investigators have assessed the effects of noise on cognitive function and behavioural symptoms in children (Crombie et al., 2011; Dreger et al., 2015), fewer yet have explored the mental health consequences of noise in adults. Although studies that target adults have produced conflicting results, infrequently, residential noise exposure has been associated with anxiety (Stansfeld et al., 1996; Standing and Stace, 1980; Edsell, 1976). An early review acknowledged that emotional and psychological deficits stemming from noise annoyance can, in the long term, lead to help-seeking responses, including the use of sleep medication and anxiolytic and anxiolytic drugs (Westman and Walters, 1981). A few studies preceding this review had reported increased mental-hospital admissions in association with aircraft noise exposure (Abey-Wickrama et al., 1970; Meecham and Smith, 1977).

Existing studies on the mental health effects of road-traffic noise have mostly used modelled (Brink, 2011; Orban et al., 2016; Fyhri and Aasvang, 2010; Sygna et al., 2014) or measured (Öhrström, 2004; Stansfeld et al., 1996; Öhrström and Björkman, 1983) noise to assess exposure. However, it is generally acknowledged that individual noise perception varies between persons, and perception by the same person changes over time. Noise perception is not always determined by sound pressure level, it also hinges upon the quality and context of the sound stimulus, current activity and engagements of the recipient, individual temperament, cognitive style, state of mind and health, level of control over the sound stimulus, attitude toward sound source etc., which all give meaning and interpretation to incipient sound (Westman and Walters, 1981; Basner et al., 2013). Noise annoyance is an expression of psychological strain due to noise. By estimating noise annoyance, individual differences in noise perception and the ensuing effects can be considered. This study aims to determine how road-traffic noise affects mental health indicators, namely: sedative, anxiolytic and antidepressant use. We also compare the effects of noise annoyance and modelled noise on these indicators.

2. Methods

2.1. Study design and participants

The Helsinki Capital Region Environmental Health Survey was conducted in the Helsinki metropolitan area, which comprises Helsinki, Espoo and Vantaa. The survey was carried out to evaluate perceived exposures to specific environmental factors by residents and their views of the possible health risks caused by the environment. The survey assessed health risks associated with noise and air pollution and also the health benefits that are derived from access to green areas. Additionally, some medical history and data on confounders were collected to facilitate epidemiological analysis. The survey questionnaire had 93 questions and numerous subquestions. The survey was conducted in two phases: first, in the city of Helsinki from the latter part of May to August 2015, and, second, in the cities of Espoo and Vantaa from June to August 2016. Eight-thousand Helsinki residents age 25 years and above were selected from the Population Registry of Finland using simple random sampling in 2015. Similarly, 4000 residents of Espoo and 4000 residents of Vantaa were sampled in 2016, yielding, in total, 16,000 residents. Potential respondents were contacted by post and invited to fill a self-administered questionnaire, which they could choose to complete electronically or on paper. This sample consisted of 53% women and 47% men. A single reminder was sent to non-respondents. The response rate was 47% in 2015 and 45% in 2016.

2.2. Exposure

Noise annoyance was assessed using the questionnaire item, '*Are you usually disturbed or your concentration disturbed or annoyed by road-traffic noise when you are at home, indoor and the windows are closed?*' Anchors to this question were: i) no annoyance; ii) slight annoyance; iii) some annoyance; iv) severe annoyance; v) extremely annoyance. To facilitate statistical analysis, respondents were then divided into two groups: 'none to mild annoyance' (no annoyance and slight annoyance) and 'moderate to severe annoyance' (some annoyance, severe annoyance and extreme annoyance). Residential exposure to road-traffic noise was estimated from façade noise maps, which were modelled by a consulting company, Sito, for the Helsinki Capital Region (Oy, 2012). Road-traffic noise was estimated in accordance with the EU Environmental Noise Directive 2002/49/EC (EEC, 2002) using the Nordic prediction method (TemaNord 1996:525) (Nielson et al., 1996) for major highways and the main and collector streets within an area (Nielson et al., 1996). Input variables for the noise model include terrain characteristics, ground surface, buildings and noise barriers and traffic flow, speed and proportion of heavy vehicles for the year 2011. The 2011 estimates remain valid because land-use and traffic changes in the latter years have been insufficient to significantly alter façade noise levels (Supplement S1). The highest L_{den} on façade points within 20 m of residents' home address coordinates was used as the exposure estimates. L_{den} is the A-weighted day-evening-night equivalent continuous sound level calculated over a 24-hour period. A 10 dB penalty was added to the levels between 22.00 and 07.00 h, and a 5 dB penalty was added to the levels between 19.00 and 22.00 h to reflect people's extra sensitivity to noise during the night and the evening. Noise modelling was based on 2011 data; thus, newer buildings—74 (6%) out of 5931 sampled buildings—had missing façade noise values.

2.3. Outcome variables

The use of sleep medication, anxiolytics and antidepressants were elicited in the survey as proxy measures for sleep disorders, anxiety disorders and depression. We used the single question, '*When did you last take the following medication?*' Listed among the medications were sleeping pills, tranquilizers and antidepressants. Against each medication, respondents were asked to select from the following options: '*during the past week,*' '*1–4 weeks ago,*' '*1–12 months ago,*' '*over a year ago*' and '*never*'. Respondents selecting the last two options were considered free of the outcome. As usage of psychotropic medication in Finland is entirely prescription-based, we consider this a reliable approach for assessing our index outcomes.

2.4. Individual-level covariates

We decided on confounder models a priori: variables likely to be associated with both the exposure and outcome based on published literature or rational judgement were included as confounders. Sociodemographic data included age, sex, marital status, employment status and household income level (average yearly income before taxes). Details on lifestyle factors, including alcohol consumption, current smoking status, weekly frequency of leisure-time physical activity and pet ownership, were obtained from respondents. Pet ownership is considered to be a potential confounder: persons with dogs (and to lesser extent cats) are probably more likely to choose residential areas with more access to green space and less traffic. Such residential settings would foster lower noise exposure. Pet ownership is also associated with our outcome indices because of the direct value of ameliorating mental stress, while dog ownership indirectly affects outcomes by the motivation for increased physical exercise. On the other hand, persons already living in areas that are prone to heavy traffic may avoid pet ownership because of the paucity of green space. In this scenario, pet ownership is dependent on exposure and, therefore, should not be considered as a confounder. This reasoning was taken into account in a sensitivity analysis.

Some variables, which were not included in the main confounder models, were tested for effect modification. These were: sleep disturbance from road-traffic noise, noise sensitivity and orientation of bedroom windows (if windows faced streets or not). Noise sensitivity was measured using 11 items from the Weinstein noise sensitivity scale (Weinstein, 1978). Seven of these items were reverse scored, and an aggregate score was derived for each respondent. The aggregate sensitivity scores ranged from 11 to 55. Additional information on how variables were evaluated and categorised is provided in supplement S2.

2.5. Statistical analysis

We used a binary logistic regression to assess associations between noise annoyance or modelled noise and psychotropic medication use. Each outcome variable was dichotomised from the original five response categories. We implemented several statistical models to examine relationships that specify psychotropic medication use relative to annoyance and modelled noise exposures. The first model was a crude model in which noise annoyance and modelled noise were separately examined as explanatory variables for sedative, anxiolytic or antidepressant use while controlling only for sex and age. In the main model, we controlled for more covariates, including sex, age, marital status, employment status, household income, alcohol intake, current smoking status, level of physical activity and pet ownership. Because almost all respondents lived in urban areas, there was no justification to control for urbanity in statistical models.

Modelled noise is the objective noise measure and forms the basis for stronger conclusions on relationships. It is only appropriate to use modelled noise for further sensitivity testing of our statistical models. Some sensitivity models included variables that were considered to potentially intervene on the pathway from exposure to effect. These were, therefore, not included in the main model to avoid over-adjustment. These variables were as follows: noise annoyance, noise sensitivity, sleep disturbance, bedroom window orientation, BMI and presence of chronic disease. In addition, a sensitivity model was run without pet ownership. These models were tested for robustness of results. Noise sensitivity, sleep disturbance, bedroom window orientation were tested for significant multiplicative interactions using the Wald chi-square test. Only variables that interacted with modelled noise were used in stratified analysis, while others were adjusted for as confounders.

For the purposes of statistical modelling, residential noise levels were categorised into 5 groups: $L_{den} \leq 45$ dB, 45.1–50 dB, 50.1–55 dB, 55.1–60 dB and ≥ 60 dB; age was inputted into the model as a continuous variable. A thin-plate regression spline function was applied to age because it did not relate in a linear fashion with (the log odds) of any selected outcome (Miedema and Vos, 2007). Model smoothing was done using the function in the mgcv library of the R software (Wood, 2011).

We conducted further sensitivity analyses by separating the highest exposure category (>60 dB) into two categories (60.1–65 dB and >65 dB), and we used this in the main model. Additionally, we repeated the main model but replaced categorised modelled noise levels with the original continuous form of the variable, and we included a smooth term to assess the shape of the exposure-response function. Different degrees of freedom were tested for smooth terms. We assessed multicollinearity between covariates. Post-hoc diagnostics did not reveal whether any regressor data point exerted a high influence on outcome estimates. Statistical analysis was done in the R computing environment, version 3.3.3 (R Core Team, 2017). All analyses were conducted on a 95% confidence level, and odds ratios were reported as estimates of risk.

3. Results

Overall, 7321 valid records were obtained from study participants, giving a response rate of about 50% for women and 41% for men. The response rate according to the 5th, 25th, 50th, 75th and 95th age percentiles were 29%, 41%, 56%, 68% and 81%, respectively. The majority, 3749 (51%) (from a general population of 635,181), of respondents lived in Helsinki, with 1785 (24%) (from a general population of 274,583) and 1784 (24%) (from a general population of 219,341) of respondents residing in Espoo and Vantaa, respectively. In total, 6558 (90%) respondents had data on both noise annoyance and modelled noise for their residential addresses. Stratifying this by municipality gives 3425 (52%) in Helsinki, 1608 (25%) in Espoo and 1525 (23%) in Vantaa. There were 5860 (80%) records with no missing exposure or confounder data. Forty-three percent of the study participants were males, and the mean age of participants was 55 years (Table 1). About 58% of the respondents were employed at the time of the study. Proportionally, the respondents who were moderately or severely annoyed by noise were 4% in the least exposed (≤ 45 dB) compared to 19% in the most exposed (>60 dB) noise categories (Table 1). There were fewer severely noise sensitive persons residing in places with the highest noise exposure compared to that in less exposed neighbourhoods (Table 1). The proportion of participants taking either sleep medication, anxiolytics or antidepressants was approximately 15%, 7% and 7%, respectively. The proportion of respondents who took more than one of these medications in any combination was $<2.5\%$.

The highest category of modelled noise was associated with both anxiolytic use and antidepressant use in the crude model. Noise annoyance was also associated with anxiolytic use in the crude model, but its association with sleep medication or antidepressant use was less clear. In the main model, modelled noise suggested an association with both anxiolytic use (with an exposure-response gradient) and antidepressant use. The main model also revealed that noise annoyance increased the odds of anxiolytic use by about 41% and retained the suggestive association with sleep medication use (Table 2).

In the sensitivity models, neither noise sensitivity nor sleep disturbance interacted with modelled noise. There was borderline association between the highest noise exposure category and anxiolytic or antidepressant use in the model, which included noise sensitivity (Table 3). Adding either noise sensitivity or sleep disturbance to the main model did not dramatically change the odds ratios for modelled noise, but there was evidence of negative confounding by noise sensitivity as controlling for noise sensitivity yielded increased odds ratios. Noise sensitivity was associated with increased use of all psychotropic medication. Modelled noise showed similar relationships with slightly

Table 1
Descriptive statistics of study participants by road-traffic noise level.

	N[a]	%	Road traffic noise, dB (L_{den})									
			≤45 (N[a] = 880)		45.1–50 (N = 1267)		50.1–55 (N = 1346)		55.1–60 (N = 1136)		> 60 (N = 1231)	
			n[b]	%	n	%	n	%	n	%	n	%
Age[c]	5860		55.0	(15.4)	54.5	(15.6)	54.5	(15.9)	54.4	(16.5)	53.5	(16.6)
Sex	5860											
Female	3363	57.4	518	58.9	745	58.8	716	53.2	683	60.1	701	56.9
Male	2497	42.6	362	41.1	522	41.2	630	46.8	453	39.9	530	43.1
Marital status	5860											
Single	1026	17.5	132	15.0	223	17.6	212	15.8	208	18.3	251	20.4
Married/registered relationship/ cohabiting	3822	65.2	593	67.4	846	66.8	908	67.5	722	63.6	753	61.2
Divorced/separated/widowed	1012	17.3	155	17.6	198	15.6	226	16.8	206	18.1	227	18.4
Employment status	5860											
Employed	3389	57.8	529	60.1	734	57.9	784	58.2	642	56.5	700	56.9
Not employed	2471	42.2	351	39.9	533	42.1	562	41.8	494	43.5	531	43.1
Income	5860											
< €30,001	1503	25.6	205	23.3	326	25.7	318	23.6	313	27.6	341	27.7
€30,001–€50,000	1477	25.2	214	24.3	310	24.5	336	25.0	297	26.1	320	26.0
50,001–€90,000	1808	30.9	259	29.4	386	30.5	433	32.2	337	29.7	393	31.9
≥€90,001	1072	18.3	202	23.0	245	19.3	259	19.2	189	16.6	177	14.4
Noise sensitivity	5860											
Mild	1535	27.6	224	27.1	320	26.4	352	27.7	285	26.4	354	30.0
Moderate	2808	50.4	409	49.5	590	48.7	646	50.9	552	51.1	611	51.7
Severe	1225	22.0	193	23.4	302	24.9	271	21.4	243	22.5	216	18.3
Noise annoyance	5860											
None to mild	5321	90.8	843	95.8	1196	94.4	1268	94.2	1021	89.9	993	80.7
Moderate to severe	539	9.2	37	4.2	71	5.6	78	5.8	115	10.1	238	19.3
Sleep disturbance from noise	5860											
None	4593	79.1	748	86.1	1073	85.2	1107	83.0	864	76.9	801	65.5
Slight	817	14.1	102	11.7	135	10.7	166	12.4	176	15.7	238	19.5
Moderate to severe	400	6.9	19	2.2	52	4.1	61	4.6	84	7.5	184	15.0
Orientation of bedroom windows	5860											
Facing yard	3783	65.4	586	67.3	863	68.7	910	68.7	753	67.1	671	55.4
Facing street	2003	34.6	285	32.7	393	31.3	415	31.3	369	32.9	541	44.6

[a] N (capitalized n) denotes the number of respondents within each L_{den} category or the total in each category of covariates.
[b] n (lower-case n) denotes the distribution of response categories for each covariate within strata of L_{den}.
[c] Figures presented here represent mean (standard deviation).

Table 2
Odds ratios (OR) for associations of perceived and modelled road-traffic noise (L_{den}) with use of sleep medication, anxiolytics and antidepressants.

			Medicated n (%)	Crude OR[a] (95% CI)	Adjusted OR[b] (95% CI)
Sleep medication (n = 5713)	Modelled noise	≤45 dB	119 (14.1)	1	1
		45.1–50 dB	194 (15.7)	1.15 (0.89–1.47)	1.17 (0.87–1.45)
		50.1–55 dB	182 (13.9)	1.00 (0.78–1.29)	0.99 (0.77–1.28)
		55.1–60 dB	168 (15.1)	1.08 (0.80–1.33)	1.06 (0.81–1.37)
		> 60 dB	174 (14.4)	1.03 (0.80–1.33)	0.97 (0.75–1.26)
	Noise	Slight or none	754 (14.5)	1	1
	Annoyance	Moderate to severe	83 (15.8)	1.20 (0.93–1.54)	1.17 (0.91–1.51)
Anxiolytics (n = 5687)	Modelled noise	≤45 dB	48 (5.7)	1	1
		45.1–50 dB	82 (6.7)	1.18 (0.81–1.70)	1.12 (0.77–1.63)
		50.1–55 dB	82 (6.3)	1.11 (0.77–1.60)	1.09 (0.75–1.58)
		55.1–60 dB	79 (7.2)	1.26 (0.87–1.82)	1.24 (0.85–1.82)
		> 60 dB	101 (8.4)	1.48 (1.03–2.11)	1.34 (0.93–1.93)
	Noise	Slight or none	343 (6.6)	1	1
	Annoyance	Moderate to severe	49 (9.4)	1.49 (1.09–2.05)	1.41 (1.02–1.95)
Antidepressants (n = 5688)	Modelled noise	≤45 dB	49 (5.8)	1	1
		45.1–50 dB	86 (7.0)	1.23 (0.85–1.76)	1.20 (0.83–1.73)
		50.1–55 dB	84 (6.4)	1.15 (0.80–1.65)	1.13 (0.78–1.64)
		55.1–60 dB	66 (6.0)	1.04 (0.71–1.53)	1.04 (0.70–1.53)
		> 60 dB	97 (8.1)	1.43 (1.00–2.04)	1.32 (0.91–1.90)
	Noise	Slight or none	339 (6.69)	1	1
	Annoyance	Moderate to severe	43 (8.2)	1.26 (0.91–1.76)	1.15 (0.82–1.63)

[a] Crude model adjusted only for age and sex.
[b] Adjusted for sex, age, marital status, employment status, household income, alcohol intake, current smoking status, level of physical activity and pet ownership.

Table 3
Odds ratios (OR) of associations of modelled road-traffic noise (L_{den}) with use of sleep medication, anxiolytics and antidepressants.

Noise exposure	Sleep medication use		Anxiolytic use		Antidepressant use	
	OR	95% CI	OR	95% CI	OR	95% CI
Sensitivity model[a]	n = 5453		n = 5438		n = 5440	
Modelled noise exposure						
≤ 45 dB	1		1		1	
45.1–50 dB	1.14	0.87–1.48	1.17	0.79–1.73	1.23	0.83–1.81
50.1–55 dB	1.05	0.80–1.37	1.13	0.76–1.67	1.19	0.81–1.76
55.1–60 dB	1.13	0.86–1.48	1.22	0.82–1.81	1.05	0.70–1.57
> 60 dB	1.04	0.79–1.37	1.46	0.99–2.13	1.42	0.97–2.08
Noise sensitivity						
Mild	1		1		1	
Moderate	1.37	1.12–1.69	1.34	1.01–1.77	1.40	1.04–1.87
Severe	2.71	2.16–3.39	2.22	1.63–3.04	2.11	1.53–2.92
Sensitivity model[b]	n = 5666		n = 5640		n = 5642	
Modelled noise exposure						
≤ 45 dB	1		1		1	
45.1–50 dB	1.14	0.88–1.47	1.14	0.77–1.66	1.23	0.85–1.80
50.1–55 dB	1.01	0.78–1.31	1.09	0.75–1.60	1.17	0.80–1.72
55.1–60 dB	1.04	0.80–1.36	1.18	0.80–1.75	1.00	0.67–1.49
> 60 dB	0.93	0.71–1.21	1.32	0.90–1.92	1.32	0.91–1.93
Sleep disturbance						
None	1		1		1	
Slight	1.00	0.80–1.26	0.90	0.65–1.24	0.82	0.59–1.14
Moderate to severe	1.75	1.33–2.31	1.50	1.03–2.17	1.25	0.85–1.83

[a] Adjusted for sex, age, marital status, employment status, household income, alcohol intake, current smoking status, level of physical activity, pet ownership and noise sensitivity.

[b] Adjusted for sex, age, marital status, employment status, household income, alcohol intake, current smoking status, level of physical activity, pet ownership and sleep disturbance.

lower odds ratios in the sensitivity model that included sleep disturbance. Sleep disturbances showed a stronger association with sleep medication than it did with anxiolytic use. Statistical relationships remained unchanged when either BMI or the presence of chronic illness was added to the main model or when the six-category substitute of the modelled noise variable was used in the analysis (results not shown). Removal of pet ownership from the main model yielded minimal changes to model estimates (Table S6). Similarly, the addition of noise annoyance to the model without pet ownership gave no meaningful change in the estimates for modelled noise (Table S6).

The spline plots showed that modelled continuous noise seemed to have a linear relationship with psychotropic medication use (Fig. S3). Exploring this relationship in a linear model showed that for a 5 dB increase in noise, corresponding odds ratios were 0.99 (95% CI, 0.95–1.04), 1.04 (95% CI, 0.98–1.11) and 1.03 (95% CI, 0.97–1.10) for taking sleep medication, anxiolytics and antidepressants, respectively.

Only the orientation of bedroom windows interacted with noise to increase the odds of using antidepressants ($X^2 = 10.5$, $df = 4$, $p = 0.032$) (Table S5). Among the respondents whose bedroom windows faced the street, modelled noise was strongly associated with increased antidepressant use, showing about 200% higher odds in the highest exposure category (Table S7).

4. Discussion

Our study found that modelled noise showed a suggestive association with anxiolytic and antidepressant use, but not with sleep medication. Noise annoyance was associated with increased drug use for anxiety and was less clearly associated with sleep medication use. Modelled noise was significantly associated with increased odds of antidepressant use in respondents whose bedroom windows faced the street. There was no association between road-traffic noise exposure and sleep medication use. Noise sensitivity was not an effect modifier, but was associated with all psychotropic medication use.

4.1. Road-traffic noise and anxiolytic use

Noise annoyance was significantly associated with increased anxiolytic medication. Additionally, the highest category of modelled noise showed a suggestive association with anxiolytic use in the main model and the sensitivity model, which included noise sensitivity. Early experimental studies highlighted the effects of noise on state anxiety (Standing and Stace, 1980; Edsell, 1976). These studies showed that noise exposure accentuated state (temporary) anxiety score but showed no effect on trait (chronic) anxiety (Standing et al., 1990). Later studies found a positive association between night-time road traffic noise and either an increased anxiety score (Stansfeld et al., 1996) or a higher procurement of anxiolytic medication by privileged people (Bocquier et al., 2014). The latter finding was not replicated in other study populations (Floud et al., 2013; Orban et al., 2016).

Anxiety is characterised by worry. In severe cases, it often manifests as somatic symptoms and can limit the capacity for normal daily function (Stein and Sareen, 2015). Anxiety can be transient and connected to specific life events or experiences, in which case it is categorised as state anxiety, or it may be chronic and excessive, as occurs in trait anxiety. Treatment may be initiated for state anxiety where an offending stimulus, such as noise, persists or when state anxiety is associated with other medical conditions. Noise-stress response occurs via the endocrine activation of the hypothalamo-pituitary-adrenocortical axis, which causes the release of cortisol, and autonomic activation of the sympathetic nervous system. Stress, which is so induced, is thought to create a feedback loop to the amygdala, which upregulates the corticotrophin-releasing factor and its receptors, leading to the manifestation of anxiety symptoms (Eraslan et al., 2015; Spreng, 2000).

4.2. Road-traffic noise and sleep medication

We did not observe any clear association between road-traffic noise and uptake of sleep medication. An earlier study in Finland supports this observation (Halonen et al., 2012). Findings elsewhere also show that although outside night-time noise was associated with poor sleep quality, it was not associated with sleep medication (de Kluizenaar et al., 2009; Evandt et al., 2017). Insulation against road-traffic noise provided by double- or triple-glazed windows, which are primarily designed to retain indoor heat during winter, likely explains this finding. A report from Finland suggests that in Nordic countries, airborne sound insulation of building facade typically varies between 30 dB to 50 dB (Saarinen, 2002). This report has been supported by independent findings from Denmark and Norway, where similar window specifications have led to considerable indoor attenuation of façade noise levels (Öhrström and Björkman, 1983; Bendtsen, 1999).

4.3. Road-traffic noise and antidepressants

Modelled noise showed a weak association with antidepressant use in the main model, but was more clearly associated with an increased use of antidepressants in respondents whose bedroom windows were oriented toward the street. However, since stratification did not yield any effect with anxiolytic use, this finding should be viewed with caution. Although some authors have found a positive association between road-traffic noise and indicators of depression (Orban et al., 2016; Seidler et al., 2017; Yoshida et al., 1997), this has not always been the case (Stansfeld et al., 1996). Mixed findings are reported in studies that measured mental health outcomes differently, for example, use of an inventory that indistinctly evaluates anxiety and depression (Hammersen et al., 2016; Sygna et al., 2014) or use of an audit instrument that collectively assesses anxiolytic and antidepressant use (Watkins et al., 2009; Halonen et al., 2014). Unavoidably, these methods combine anxiety and depression as a singular outcome, and their results do not directly compare with the present study. Admittedly, the symptoms of depression overlap considerably with that of anxiety. Differences in study findings can result from nuanced variations in the way exposures and outcomes are conceptualised and estimated. Inconsistencies can also arise from inherent differences in the populations studied, predominant noise levels, building types and insulation in study settings.

4.4. Noise sensitivity

Noise sensitivity was expected to modify the effect of noise exposure, but paradoxically, no modification was detected in this study. Rather, we found an independent association with psychotropic medication use. This observation is in line with other studies (Stansfeld et al., 1985; Stansfeld et al., 2000). Possible explanations for this could be that: First, noise-sensitive persons may be more sensitive to other stressors which mask the effect of noise. Noise sensitive persons are generally more conscious of their environments and are more susceptible to stress and worry (Miedema and Vos, 2003). Relationships between noise sensitivity and anxiety have been acknowledged (Park et al., 2017; Iwata, 1984) with the implication that noise sensitivity may positively co-vary with anxiety without the influence of a noise source (Persson et al., 2007). Second, noise-sensitive people may selectively reside in quieter parts of town thereby minimising the influence of higher exposure. There is slight evidence that severely noise-sensitive respondents in our study sample tended to live in less noisy areas. We also observed that about 18% of the residents in areas with noise > 60 dB were severely noise sensitive. These people may have chosen to stay in those areas because they were healthy. The inclusion of noise sensitivity increased effect estimates in the highest noise exposure category in the sensitivity model relative to the main model—pointing to a negative confounding effect.

4.5. Noise annoyance versus modelled noise

Noise annoyance was more clearly associated with anxiolytic use than with modelled noise, but weakly associated with sleep medication. The highest category of modelled noise gave higher odds for antidepressant use in than noise annoyance. Comparing the behaviours of both exposure measures in the crude and main models, no variable was consistently more associated with the outcome. Annoyance is determined by noise levels and more consistently by noise sensitivity. Noise annoyance more directly correlates with indoor noise, while modelled façade noise represents outdoor exposure. Previously, few studies have compared the relationships of noise annoyance and modelled noise to health outcomes even though combining both subjective and objective exposure has been recommended in epidemiologic studies (Babisch, 2005). Using noise annoyance as a proxy for exposure, some investigators were able to demonstrate relationships with select outcomes that are more often examined in association with objectively measured noise (Hammersen et al., 2016; Dreger et al., 2015; Babisch, 1998; Lercher et al., 1993; Meijer et al., 1985; Pitchika et al., 2017). As aforementioned, noise annoyance is influenced by individual noise sensitivity, therefore associations between noise annoyance and outcomes of interest may more closely reflect individual sensitivity to noise rather than the absolute effect of sound energy. Noise annoyance may be the only option in large-scale population studies that incorporate human participants living in areas that are not represented on noise maps (Dzhambov and Dimitrova, 2014). Objectively measured noise is, however, preferred in epidemiologic studies because it is more valid. Modelled noise can facilitate a meaningful comparison between populations. It provides a better yardstick for assessing the immediate effects of interventions that aim to reduce noise or infrastructural changes that increase exposure levels. This is because strict values can be assigned to expected reductions in modelled noise due to interventions, while annoyance levels can vary on the same noise levels and may exaggerate the actual noise reduction (Öhrström, 2004; Amundsen et al., 2013). Annoyance, on the other hand, will provide an indication of the long-term consequence of interventions and the satisfaction of local populations with interventions (Amundsen et al., 2013).

4.6. Strengths and weaknesses

Our study strength includes a relatively large study population and the use of two indicators of noise exposure: noise annoyance and modelled noise, the latter being the more objective measure of exposure. Noise annoyance is not only an indicator of noise exposure but also represents an effect. It can be argued that annoyance has the advantage of representing indoor exposure more closely, and it takes into account not just noise levels, but also other characteristics of noise. On the other hand, the cross-sectional design of the study does not permit one to infer whether annoyance precedes medication use or vice versa. Asking questions about medication is a relatively straightforward method. Adults typically know what conditions they are receiving medication for, even when they may not know the pharmacological classification of individual medicines. In Finland, sleeping pills, anxiolytics and antidepressants can only be obtained by prescription. Therefore, in this study, psychotropic medication use as an outcome represents a diagnosed condition requiring treatment. We administered a general environmental health questionnaire; medication use was asked in a section unrelated to any exposures. Therefore, respondents were less likely to bias their responses based on noise exposure.

The response rate in the study was relatively high by today's standards, but it may appear as a weakness because of the possibility of self-selection. Persons who are more worried about environmental exposures and consequently more annoyed by noise, for example, would probably be more likely to participate in the study. This may have increased our chances of finding an effect, but should not have created spurious associations.

Noise annoyance was not included in our main model because it may likely mediate the effects of noise exposure on medication use. However, in our sensitivity analyses, changes in effect estimates for modelled noise and annoyance were negligible when both variables were mutually adjusted for. We did not conduct an in-depth mediation analysis, but the results suggest that annoyance and modelled noise exert independent effects in this study population.

We were not able to control for road-traffic-related air pollution in this study even though it is a co-exposure with road-traffic-related noise. Evidence of an association between air pollution and physician-diagnosed or self-reported symptoms of depression has been demonstrated in several longitudinal and cross-sectional studies (Kim et al., 2016; Kioumourtzoglou et al., 2017; Lim et al., 2012; Pun et al., 2017; Vert et al., 2017). An association has also been shown between air pollution and anxiety (Power et al., 2015). Notably, none of these studies adjusted for the effect of noise. Zijlema and colleagues, in their multinational study, mutually adjusted for air pollution and noise while investigating depressive symptom score as an endpoint. Findings from this study were heterogeneous, and participants from Finland were among those in whom no association between air pollution and symptoms of depression was apparent (Zijlema et al., 2016).

5. Conclusion

In conclusion, we found some evidence of an association between either noise annoyance or modelled noise exceeding 60 dB and psychotropic medication use. There were no consistent differences between annoyance and outdoor noise in the strengths of association. Noise annoyance may find use in study areas where modelling of noise is not realistic. Noise sensitivity was associated with psychotropic medication use, but it did not modify the effect of noise. The fact that some evidence of noise effect was observed despite the effective sound insulation in buildings located in this northern study area suggests that the mental health effects of noise may be significant. This finding should stimulate similar studies in regions with different climatic conditions.

Conflicts of interest

The authors declare no conflicts of interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2018.06.034.

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