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Health effects from low-frequency noise and infrasound in the general population: Is it time to listen? A systematic review of observational studies

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HIGHLIGHTS

A part of the population reports high annoyance attributed to LFN sources.

LFN is associated with self-reported outcomes, mainly neurological.

Current evidence is very limited, especially regarding chronic conditions.

More epidemiological research on LFN and health effects is needed.

ABSTRACT

A systematic review of observational studies was conducted to assess the association between everyday life low-frequency noise (LFN) components, including infrasound and health effects in the general population. Literature databases Pubmed, Embase and PsycInfo and additional bibliographic sources such as reference sections of key publications and journal databases were searched for peer-reviewed studies published from 2000 to 2015. Seven studies met the inclusion criteria. Most of them examined subjective annoyance as primary outcome. The adequacy of provided information in the included papers and methodological quality of studies was also addressed. Moreover, studies were screened for meta-analysis eligibility. Some associations were observed between exposure to LFN and annoyance, sleep-related problems, concentration difficulties and headache in the adult population living in the vicinity of a range of LFN sources. However, evidence, especially in relation to chronic medical conditions, was very limited. The estimated pooled prevalence of high subjective annoyance attributed to LFN was about 10%. Epidemiological research on LFN and health effects is scarce and suffers from methodological shortcomings. Low frequency noise in the everyday environment constitutes an issue that requires more research attention, particularly for people living in the vicinity of relevant sources.

GRAPHICAL ABSTRACT

1. INTRODUCTION

Unlike several other environmental stressors, noise pollution, especially in the urban environment, is still increasing (Öhrström et al., 2006; WHO, 2011). Well-documented evidence supports an association between higher levels of environmental noise and various adverse health effects, such as cardiovascular diseases (Münzel et al., 2014), sleep quality (de Kluizenaar et al., 2009; Omlin et al., 2011; van Kamp and Davies, 2013), annoyance (Miedema and Oudshoorn, 2001; van Kamp et al., 2004; Frei et al., 2014) and also cognitive development and hyperactivity in vulnerable population groups such as children (van Kamp and Davies, 2013; Basner et al., 2014).

Noise ranks among the environmental stressors with the highest public health impact (WHO, 2011) and it is therefore important to regularly monitor for the determination and comprehension of possible effects on health. An underinvestigated noise component in relation to health effects is low frequency noise (LFN) (sound below 250 Hz), including infrasound (up to 20 Hz) (Berglund et al., 1996; Leventhall, 2004). Although LFN is audible at sufficiently high pressure levels (decibels, dB), it can also occur below the human hearing threshold (Leventhall, 2007), considering that the human ear responds better to sound frequencies between 500 Hz and 8 kHz (Farina, 2014).

Sounds within the low-frequency sound spectrum comprise a common, everyday-life environmental exposure, produced by natural (sea waves, wind turbulence) as well as by man-made sources (industrial installations, domestic appliances, transportation) sources. The latter constitute the primary cause of LFN (Berglund et al., 1996), while the rapid expansion of infrastructure has increased the attribution of symptoms to LFN and public concern (Jakobsen, 2012). According to earlier evidence from local environmental health authorities, complaints due to LFN comprise about 35% of the total noise complaints filed (Bengtsson and Waye, 2003). Low frequency noise in the residential environment is described as a constant, deep and humming/rumbling sound and although complainants perceive it with their ears, the perception of bodily or external vibration is also possible (Møller and Lydolf, 2003). Annoyance is usually the first reaction to this type of noise, often accompanied by secondary effects, such as headache, concentration difficulties palpitations and sleep problems (Møller and Lydolf, 2003; Leventhall, 2009).

A number of studies suggest an association between LFN and various physiological and psychological reactions such as annoyance, hearing threshold shift, concentration problems, lower sleep quality, mood effects (Persson Waye et al., 1997; Ising and Ising, 2002; Leventhall, 2004; Pawlaczyk-Łuszczyńska et al., 2005) and also controversial conditions such as the so-called vibro-acoustic disease (Alves-Pereira and Branco, 2007; Chapman and St George, 2013). Additionally, adverse health effects from occupational exposure have been observed on memory, annoyance and performance (Gomes et al., 1999; Persson Waye et al., 2001; Bengtsson et al., 2004; Kaczmarska and Łuczak, 2007; Pawlaczyk-Luszczynska et al., 2009). Evidence on vascular and respiratory effects is inconclusive (Schust, 2004).

Although the potential impact of LFN as environmental pollutant has been highlighted by the WHO (Berglund et al., 1999), current evidence is mainly based on case studies and laboratory experiments of small sample sizes and short exposure sessions (Leventhall, 2009; Ambrose et al., 2012). It is therefore unknown to what extent such health effects occur in relation to everyday-life exposure to LFN at the population level. Observational studies are highly important due to the investigation of everyday-life exposure and effects in larger samples.

No systematic evaluation of the peer-reviewed observational epidemiological literature has been performed up to date on the association between LFN and health. The present paper aims to fill this gap in the literature.

2. Methods

2.1. Data sources and search

Pubmed, Embase and PsycInfo were searched as primary databases for relevant studies published between January 1st, 2000 and January 30th, 2015. There was no a-priori language restriction.

A wide range of (combined) keywords was used, related to environmental noise exposure and health effects, presented in Table 1. In addition to the electronic database searches, the reference sections of previous systematic reviews and key papers were examined. The databases of the following relevant journals were also searched: Noise and Health, The Journal of the Acoustical Society of America, Journal of Low Frequency Noise, Vibration and Active control, Journal of Environmental Psychology.

[TABLE 1]

2.2. Inclusion criteria

For paper selection, four criteria were used:

I. *An exposure criterion*. Only studies examining health effects in relation to exposure to low-frequency noise and/or infrasound (up to 250 Hz) in the general population were considered as eligible for the review. Exposure characterization based on self-reported questionnaires was considered acceptable as long as this was explicitly stated. Studies on occupational exposure are not covered in this review.

II. A health outcome criterion. Eligible studies should assess any health indicators (e.g annoyance, symptomatic reactions, physical/mental health, well-being/quality of life indicators, medical disorders), on the basis of self-reports or objective measures.

III. *A population criterion*. The eligible studies recruited samples of healthy individuals being at least 15 years old. Studies on individuals with self-reported noise sensitivity were considered eligible as well.

IV. *A study criterion*. Only peer-reviewed articles of primary observational studies (not re-analyses of outdated data, unpublished reports, conference proceedings, commentaries or reviews), investigating a potential exposure–response relationship were considered as suitable for the present review.
Studies in which exposure was manipulated, such as laboratory studies and "natural experiments", were not included. Case-studies were excluded as well.

2.3. PROCEDURE

The literature search, evaluation of inclusion and exclusion criteria, data extraction were conducted by the first author, with uncertainties resolved through consultation with the rest of the co-authors. More specifically:
1) In the first stage the titles and abstracts that were derived from the search process were screened in terms of relevance
2) The hard copies of potentially relevant publications were assessed, using the pre-established inclusion criteria
3) Data were extracted
4) The study quality evaluation was performed independently by the first two authors.
5) Screening for meta-analysis was independently conducted by the first two authors.

For each eligible study, the following data were abstracted: Reference and country, study design, sample characteristics and response rate, source of noise and exposure assessment, outcome assessment, variables included as potential confounders, source of funding, and statistically significant exposure-outcome associations.

2.4. Study quality assessment

A combined indicator of study quality was developed, based on criteria of methodological bias (exposure misclassification, selection bias, confounding) in observational research (Grimes and Schulz, 2002) and the adequacy of information provided in each article (e.g regarding study design, participant recruitment and characteristics, methodology for the assessment of exposure and outcome, statistical analysis) (STROBE statement, Von Elm et al., 2007). The rating method was qualitative and similar to schemes applied in previous systematic evaluations of the observational literature (Baliatsas et al., 2012). This evaluation was conducted a-posteriori and was not a prerequisite for the consideration of a study as eligible for the review.

2.5. Screening studies for meta-analysis

After data extraction and quality evaluation, the included studies were screened for meta-analysis suitability. The following possibilities were examined:

1) Conducting a descriptive meta-analysis, to estimate the prevalence of people highly annoyed by LFN, irrespective of noise exposure levels. Only two eligibility criteria were considered, in the absence of assessment of etiological associations: First, studies had to assess high subjective annoyance due to LFN or infrasound; second, the raw prevalence estimates of annoyance had to be provided in the papers or be derivable.

2) Performance of a causal meta-analysis, to gain more insight into the association between everyday life exposure to LFN and health effects.

Study eligibility criteria were the assessment of similar outcomes based on comparable measures and employment of similar methodology to assess exposure to LFN. In addition, effect estimates of the reported associations had to be available in the articles, or at least derivable. Finally, studies with a low score on one or more of the quality assessment categories would be excluded from the meta-analysis. Analyses were carried out using Comprehensive Meta-analysis (Version 2.2, Biostat, Englewood, NJ).

3. RESULTS

3.1. Literature search and study characteristics

Fig. 1 illustrates the literature search process. We examined 4014 citations in total and based on our criteria we identified 7 observational studies on the association between everyday life exposure to LFN and health effects (Table 2). All studies were of cross-sectional design and most of them were conducted in Europe (*n* = 4).

[TABLE 2][FIGURE 1]

Response rates were reported in 6 studies, ranging from 71% to 93%. Noise sources of primary concern in the investigation were ventilation systems, neighborhood/road traffic, wind turbines and aircrafts. The vast majority of the included studies used objective measurements to assess LFN (n = 6) such as spot measurements and sound propagation models. In two of these studies, exposure assessment was solely relied on A-weighting. The most frequently examined outcome was subjective annoyance (n = 4). All studies assessed health outcomes using self-reported questionnaires.

3.2. Association between everyday life LFN exposure and health effects

As shown in Table 2, two studies suggested a significant association between LFN and annoyance. Significant associations or between-group (“exposed” vs. reference group) differences were also observed for outcomes such as hypertension, heart palpitations, concentration problems and sleep-related problems. Age and gender were the most examined potential confounders. Study quality appeared to be moderate for the majority of the examined studies, on the basis of the provision of information in each article and the methodology followed to assess the LFN exposure-outcome associations (Table 3). Overall, among the most important limitations were insufficient adjustment for confounders, use of A-weighting, self-reported assessment of exposure and small sample sizes.

[TABLE 3]

3.3. Data synthesis: pooled prevalence of high annoyance in the population

Regarding the descriptive meta-analysis, four studies provided data to calculate per-study and pooled raw prevalence of high levels of subjective annoyance attributed to LFN. The studies were all performed among people living in the vicinity of some LFN source, be it an airport, wind turbines, or installations at home producing LFN/infrasound.

To summarize the prevalence estimates, DerSimonian–Laird random-effects meta-analysis (DerSimonian and Laird, 1986) was performed, considering heterogeneity among the studies, which was verified using the I^2 statistic (Higgins et al., 2003) (I^2 = 27.6%). Prevalence statistics were described based on the event rate. Ninety-five percent confidence intervals (CIs) were calculated using the sample size (n) and standard error. Prevalence of high annoyance in the studies varied between 2% and 34% with a pooled prevalence of 10.5% as shown in Table 4. Publication bias was not apparent as assessed by the Egger's test (Egger et al., 1997), which was not significant (p = 0.32).

Table 4. Prevalence of high self-reported annoyance attributed to LFN, based on data from observational studies.

Abbreviations: CI, confidence interval.

Taking all the eligibility parameters into account, it was not feasible to perform a causal meta-analysis on the association between exposure to LFN and health outcomes.

4. Discussion

4.1. Primary findings

This systematic review identified the observational epidemiological studies undertaken the past fifteen years on the association between everyday life LFN, including infrasound, and health effects in the general population. A descriptive meta-analysis was carried out as a first effort to estimate the pooled prevalence of high annoyance attributed to LFN at the level of the adult population living in the vicinity of some source of LFN. The review showed some associations between exposure to LFN sources and self-reported annoyance and various neurological symptoms such as sleep-related problems, concentration difficulties and headache. Inconsistency across studies and the small number of existing observational investigations prevents us from a direct comparison with experimental evidence (Leventhall, 2009). The pooled analysis on prevalence of subjective annoyance showed that, independently of the exposure levels, a considerable number of people living in the vicinity of noise sources attribute high annoyance to LFN. However, there is still very limited risk-assessment research in the field of LFN and health effects. More research should be undertaken in several directions, investigating health effects of objectively measured LFN from different, widespread and emerging, sources in everyday life. This requires serious methodological considerations regarding exposure characterization and outcome assessment.

4.2. Strengths and limitations

The strengths of this paper include a rigorous search strategy, consideration of different LFN sources, study quality assessment and the estimation of prevalence of high annoyance attributed to LFN components in the included studies. Among the limitations are the relatively small number of eligible studies, small sample sizes, the overall moderate quality of evidence and between-study heterogeneity, especially in relation to outcome measures. The fact that most studies only investigated self-reported symptoms in relation to exposure, limits the conclusions that could be drawn regarding other (long-term) health effects. Finally, methodological differences and study quality issues prevented us from conducting a causal meta-analysis.

4.3. Methodological considerations and implications for future research

An issue of importance in terms of exposure characterization is the weighting method used to measure LFN. A-weighting is widely used in public health research. Adapted to the sensitivity of the average human ear, sound level meters set to the A-weighting scale cannot efficiently evaluate the contribution of LFN components, since the human ear is less sensitive to very low-pitch or high-pitch noises (Farina, 2014). As a result, LFN levels are suppressed by A-weighted measures, which can lead to exposure misclassification (Farina, 2014; Ascari et al., 2015). Exposure assessment protocols for population research incorporating this aspect still need to be developed and applied. Use of personal exposure measurements apart from time-consuming is costly and therefore may not be feasible for large epidemiological studies. Exposure prediction models could be a cost-efficient approach, however, there is not enough evidence on the accuracy of low frequency mapping while large heterogeneity exists among the proposed methods (Ascari et al., 2015). An important aspect for investigation could also be the contrast or overlap between perceived and actual noise levels. Previous research on other environmental exposures such as to electromagnetic fields (EMF) has shown that objectively measured and perceived exposures do not always correspond and this could have major implications for the mechanisms that lead to symptom report (Baliatsas et al., 2015).

Studies of longitudinal design assessing exposure-outcome patterns over time and intervention studies of large samples in which manipulation of LFN levels could be examined in relation to health effects, would help us determine the causal mechanisms involved. Considering that most of the existing studies have been focusing on annoyance, outcome assessment should be expanded to more acute as well as long-term health effects based on validated instruments. Especially regarding chronic disorders, the combination of self-reported and electronic medical record data would provide reliable information into clinically relevant characteristics of the respondents and minimize the risk for biases such as outcome misclassification and selection bias. Furthermore, it is a challenge to determine the exact role of annoyance in relation to health effects of LFN, both conceptually and explanatorily; for instance, as a health outcome and/or an indicator of secondary health effects and future morbidity.

Given the various non-acoustic factors that play a role in reactions to noise (Stansfeld and Shipley, 2015), not only exposure levels that could be related to health effects are of importance, but also the confounding, mediating and/or moderating role individual aspects such as sociodemographic characteristics, noise sensitivity, environmental worries, perceived control over environmental stressors, coping strategies and somatic morbidity and somatoform disorders (van Kamp, 1990; van Kamp et al., 2004; Bailer et al., 2005; Page et al., 2006; Baliatsas et al., 2015). In addition, whether symptomatic reactions to LFN can be considered a manifestation of noise sensitivity is worthy of further investigation. Noise-sensitive groups are underrepresented in study populations and evidence on differential characteristics is scarce (van Kamp et al., 2013).

Finally, the publication of technical and health reports in peer-reviewed public health journals should be encouraged, since relevant studies of potential added value in the grey literature are difficult to identify, access and/or assess.

Moreover, as long as uncertainty regarding health effects from LFN remains, effective risk communication with the public is needed, acknowledging the worries of the affected citizens and facilitating access to the latest research findings.

5. Conclusions

Evidence from the present systematic evaluation of observational studies suggests an association between exposure to LFN components and self-reports of annoyance and various symptoms in the population. However, results should be interpreted with caution due to the small number of existing studies. An association with other health effects might exist, but evidence is still limited and inconclusive. More epidemiological research is imperative, involving larger samples and better methodological quality in terms of exposure and outcome assessment. This will also make feasible the performance of future meta-analytic studies.

Conflict of interest

None declared.

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TABLES AND FIGURES

Table 1
Key search terms.

Outcome	Physical symptoms, somatic symptoms, health symptoms, health problems, health effects, neurological symptoms, ill health, well-being, quality of life, annoyance, disturbance, discomfort, sleep quality, sleep disturbance, sleep problems, insomnia, impairment, tinnitus, vertigo, nausea, balance problems, respiratory effects, respiratory problems, vibroacoustic disease, stress, irritation, attributed symptoms, fatigue, aural pain, palpitations, cardiovascular
Exposure	Noise pollution, environmental noise, noise exposure, perceived noise, noise sensitivity, noise susceptibility, auditory sensitivity, neighborhood noise, infrastructure noise, wind turbines, compressors, wind farms, ventilation noise, power lines, transmission lines, industrial noise, electrical installations, amplified music, blasting, pumps, air-conditioning, refrigerators, fans, boilers, heating system, gas pipelines, radio sound, radio noise, impulse sound, perceived sound, transportation noise, trains, rail traffic, railway noise, air traffic noise, airport noise, aircraft noise, traffic noise, road traffic noise, cooling towers, sewerage, residential noise, domestic noise, low frequency noise, low frequency sound, lf noise, infrasound, ambient noise, background noise
Design	Observational, cross-sectional, cohort, case-control, population-based
Time period	January 2000–January 2015

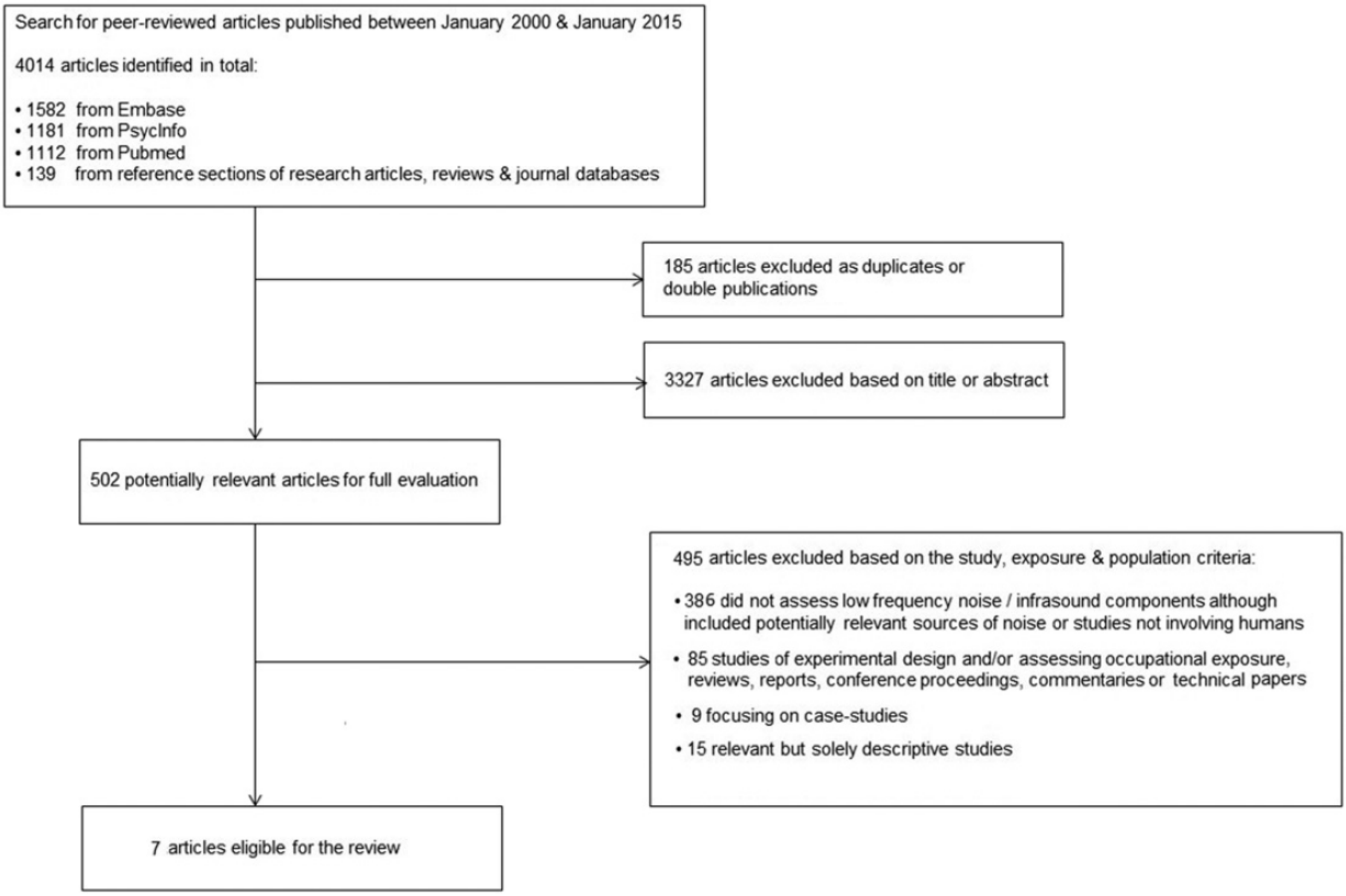

Fig. 1. Flow diagram outlining the study selection process.

Table 3
Quality assessment of observational studies on the association between LFN and health effects.

Reference	Provided information[a]	Risk for methodological bias[b]
Niven et al. (2000)	+ +	+ +
Persson Waye and Rylander (2001)	+ ++	+ +
Fidell et al. (2002)	+	+ +
Persson Waye et al. (2003)	++	+ + +
Chang et al. (2014)	+ + +	+
Dzhambov and Dimitrova (2014)	+ +	+ ++
Magari et al. (2014)	+ +	+ +

[a] + low score, + + medium score, + + + high score.
[b] + lower risk, + + medium risk, + + + higher risk.

Table 2
Observational studies on the association between LFN and infrasound exposure and health effects.

Reference & country	Study design	Sample characteristics (response rate)	Noise source(s) & exposure assessment (objective vs. self-reported)[a]	Outcome assessment	Variables considered as possible confounders	Funding source	Statistically significant associations
Niven et al. (2000), UK	Cross-sectional	947 (80%) subjects with m.a = 35.2, working in five buildings (three air-conditioned buildings, one naturally ventilated & one considered as "sick building". F.g = 49%.	LFN from air conditioning (O), spot measurements, maximum frequency level: 63 Hz, A-weighted SPL, Leq24h range in buildings = 40–74 dB.	Self-reported questionnaire on various non-specific physical symptoms.	Not reported	Unspecified	Pooled data from all buildings: itchy eyes ($p = 0.001$), stuffy nose, dry skin ($p < 0.01$). Data from the "Sick building": Runny nose ($p = 0.001$), stuffy nose ($p = 0.01$) headache, lethargy ($p < 0.01$).
Persson Waye and Rylander (2001), Sweden	Cross-sectional	279 (83%) randomly selected subjects 18–75 y.o. Six homogeneous residential areas selected, exposed to either residential LFN sources or mid-frequency noise (control areas).	Heat pumps or heat pump/ventilation systems (O), Spot measurements, Frequency spectra in LFN-exposed areas at 50–200 Hz, A-, B- & C-weighted SPL, range dB exposed vs. controls: dB(B) = 31–38 vs. 40–51; dB(C) = 41–49 vs. 49–60; dB(A)Leq24h = 44–47 vs. 44–49.	Self-reported questionnaire assessing annoyance levels & various physical and psychological symptoms.	Not reported (there was similar distribution in terms of age, gender, noise sensitivity, family status, chronic illness, employment status & workload between subjects in the exposed & control areas).	Unspecified	Prevalence range in different exposed vs. unexposed areas: Annoyance, 14.7%–20%, vs. 3.4%–4.2% ($p < 0.05$); disturbed concentration, 7.5%–17.5% vs. 0% ($p < 0.05$); disturbed rest/relaxation, 12.5%-22% vs. 0%–0.7%, ($p < 0.05$).
Persson Waye et al. (2003), Sweden	Cross-sectional	41 (71%) randomly selected subjects 18–80 y.o living in blocks of flats with one side facing a street with high traffic (comparison group) and the other side facing a courtyard full of domestic LFN sources (exposed group)	Fans, compressors, air-cooling systems (O), Spot measurements, frequency spectra at ≥20 Hz, A- & C-weighted SPL, Leq24h in whole area: dB(A) = 31(windows closed) & 43 (windows slightly opened); dB(C) = 50 (windows closed) & 56 (windows slightly opened).	Self-reported questionnaire assessing disturbance from different environmental stressors, annoyance levels, sleep quality & perceived health	Not reported (no statistically significant difference between exposed and controls in terms of age, gender, and socio-economic status.	Unspecified	N.S.
Fidell et al. (2002), USA	Cross-sectional	495 (81%) subjects ≥18 y. o, living in a residential area close an airport.	Aircraft (O), spot measurements (digital recordings), Frequency spectra at 25–80 Hz, C-weighted SPL, mean dB range in different areas = 77.5–86.9.	Telephone interviews assessing annoyance levels.	Not reported	Public	Annoyance prevalence per midpoint of LFN exposure interval: 21.6% (77.5 dB), 36.8% (87.5 dB)
Chang et al. (2014), Taiwan	Cross-sectional	820 subjects living near main roads for more than 3 years with m.a = 36 (774 controls). F.g = 51%.	Road traffic (O), Spot measurements, frequency spectra at 31.5–125 Hz, A-weighted SPL, highest median: 61 dB at 1000 Hz, lowest median: 27 dB at 31.5 Hz.	Identification of cases of hypertension based on standardized interviews.	Age, gender, body mass index and family history of hypertension, cigarette smoking, alcohol consumption, high salt intake and physical inactivity, total traffic flow rate	Public	Hypertension: at 63 Hz, median: 41 dB (OR = 2.77, 95% CI = 1.17–6.52), at 125 Hz, median: 49 dB (4.08, 95% CI = 1.57–10.63). At 125 Hz, subjects exposed to ≥51 dB vs. those exposed to <47 dB: OR = 4.65 (95% CI = 1.46–14.83).
Dzhambov and Dimitrova (2014), Bulgaria	Cross-sectional	182 (84%) subjects with m.a = 36.9, living in a non-industrial area with high levels of traffic/neighborhood noise, based on noise monitoring Municipality data. F.g = 45%.	Outdoor/neighborhood (S).	Semi-structured interview survey, assessing displaced aggression.	Age, years of residency, perceived noise sensitivity, continuous/intermittent noise exposure, frequency of hearing noises above normal threshold, interaction age * years of residency	Unspecified	Displaced aggression ($p < 0.001$)
Magari et al. (2014), USA	Cross-sectional	62 (93%) subjects with m.a = 36.9, living in and around a wind park. F.g = 43.5%.	Indoor & outdoor LFN (20–250 Hz) & infrasound (6.3–16 Hz) from wind turbines (O), sport measurements, unweighted SPL, Leq10-min = 56.9 for LFN & 60.8 for infrasound.	Self-reported questionnaire assessing annoyance levels & residential satisfaction.	General opinion on wind turbines, opinions on altered views, possible relationship between participant & operator, self-reported types of noise. In additional models: age, education, number of visible wind turbines and distance to the closest turbine.	Unspecified	N.S.

Abbreviations: LFN, low frequency noise; SPL, sound pressure levels; dB, decibel scale; Leq24h, equivalent continuous sound level; y.o, years old; F.g, female gender distribution; CI, confidence interval; OR, odds ratio; N.S., no statistical significance.
[a] O = objective exposure assessment; S = self-reported exposure assessment.

Table 4
Prevalence of high self-reported annoyance attributed to LFN, based on data from observational studies.

Study	Definition of high annoyance	No. of people annoyed	No. of participants	Prevalence % of annoyance (95% CI)
Persson Waye and Rylander (2001)	Being very annoyed to LFN from heat pump/ventilation installations	6	279	2.2 (1.0–4.7)
Fidell et al. (2002)	Being highly annoyed to LFN due to rattle and vibration produced by aircrafts	128	495	25.9 (22.0–29.9)
Persson Waye et al. (2003)	Being very or extremely annoyed by noise from fans/compressors	14	41	34.1 (21.4–49.7)
Magari et al. (2014)	Being very annoyed by LFN from wind turbines	2	62	3.2 (0.8–12.0)
Combined prevalence		150	877	10.5 (3.0–30.9)

Abbreviations: CI, confidence interval.