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Transportation noise and health in vulnerable groups in Europe: a review

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Summary

Noise research in Europe has largely focussed on children as a key vulnerable group, though other groups may also be disproportionately affected by and vulnerable to transportation noise. The aim of this report is to gain a broader understanding of whether and to what extent the effects of transportation noise exposure are higher in vulnerable groups compared to the general population. Thereby, vulnerability is viewed as function of two elements: a) susceptibility, meaning the internal factors (i.e. biological, psychological or behavioural traits) that predispose a person to be affected by noise exposure, and b) situational factors, meaning external factors or circumstances in the physical and social environment that create heightened risk of exposure. In understanding the health effects of noise in vulnerable groups, we focus on those with pre-existing health conditions and personal characteristics such as age (including elderly), sex/gender, lifestyle that may influence susceptibility as well as socioeconomic status that may be interlinked with exposure.

Relevant studies on the health effects of transportation noise were identified by means of literature search in scientific literature databases using predefined search terms. In addition, a crowd-sourcing search within the noise-health research community was conducted, given that information on potential vulnerabilities is typically included in studies as subset analyses, not always detectable within abstracts and by search terms.

Vulnerability to noise has been studied for specific health outcomes including cardiometabolic health, mental health, cognition, self-reported health status, cancer, infertility, sleep disturbance and mortality. Vulnerability factors addressed included pre-existing disease, age, sex/gender, lifestyle and behavioural factors, genetic predisposition or sociodemographic variables. Many studies included in this review identified significant effect modification for at least one of the vulnerability factors. When considered across specific vulnerability factors, however, relative risk estimates most often did not substantially differ between different population groups. Focussing on relative risk as a primary effect measure also has one key implication in terms of vulnerability — even if the relative risk is the same between groups, it would mean a higher vulnerability for people with a higher baseline disease rate. This implies that people with pre-existing cardiometabolic conditions tend to be more affected by transport-related noise, as well as older adults, for whom age-related susceptibility plays a role. These groups may require additional protection. This review also shows, however, that everyone is at risk - even the healthy. Therefore, the most effective and equitable approach is for measures to protect health should target the whole population and leave no groups out.

1 Introduction

In Europe, population groups that may be more adversely affected by environmental health hazards including transportation noise are the elderly, children and people with poor health (EEA, 2018). These individuals are biologically more susceptible to many environmental stressors, due to their age or infirmity, and may suffer a dual burden of being more vulnerable in terms of exposure to noise. Likewise, population groups with lower socio-economic status tend to be more impacted by environmental hazards, through living and working in areas with higher exposures.

In this report, **vulnerability** is viewed as function of two elements. **A) Susceptibility**, or sensitivity, refers to internal factors (i.e. biological, psychological) that predispose one to be more affected, in this case, by noise exposure. Susceptibility therefore includes factors such as pre-existing medical conditions, age, gender and individual behaviours. **B) Situational factors**, on the other hand, refer to external factors or circumstances in the physical and social environment that create heightened risk of exposure. This includes, for example, socioeconomic status, awareness about environmental pollution, access to care, and occupational hazards/shift work. We mainly focus on the first function of vulnerability (i.e. susceptibility) (chapter 3), and cover exposure and coping capacity in less detail in chapter 4 given the prior report mentioned above (EEA, 2018). Thus, the emphasis is on identifying the vulnerable groups that may need extra protection from the harmful effects of noise to ensure equity in Europe. Where evidence exists, we also treat socioeconomic status as a factor moderating the severity of the negative impacts of noise.

Against this background, the 2018 World Health Organization Environmental Noise Guidelines (ENG) for Europe (WHO, 2018) defined, as an inclusion criteria, “specific segments of the population particularly at risk (children or vulnerable groups)”. Although this was intended to include the chronically ill and the elderly, the available evidence at the time was limited to children and their potential cognitive impairment due to environmental noise exposure in the learning environment meaning primarily at schools. The scope of this report is to collate a boarder understanding of whether there are susceptible groups to noise and determine if other situational factors from the physical and social environment exacerbate the severity of the health impacts of noise.

2 Methods

2.1 Objectives

This report aims to review and synthesize the scientific literature to address the following research questions:

- Does transport noise exacerbate certain health outcomes in specific vulnerable groups (e.g., individuals with pre-existing health conditions, including mental health issues and cardio-metabolic disorders)?
- Which groups are identified as more vulnerable to noise based on current literature?
- Which groups are disproportionally exposed to noise and thus are more affected by noise?
- Are existing WHO recommendations adequate for protecting vulnerable groups, or would lower limits be more appropriate?
- What are the policy implications of the findings?

2.2 Literature review approach

A systematic search was not conducted as few studies to date are specifically on the topic of vulnerability, in terms of susceptibility, to environmental noise. Rather such information is typically included in published studies as subset analyses, not always detectable within abstracts and by search terms. Thus, a scan of recent literature within the author personal reference databases, plus crowd-

sourcing within the noise-health community, were used to identify relevant studies on the health effects of transportation noise. The author databases comprised studies on the health effects of transportation noise identified via a literature search in PubMed using predefined search terms including transportation noise (i.e. road, rail and aircraft) and health effects. For crowd-sourcing, members of the International Commission on the Biological Effects of Noise (ICBEN) Team 3 on non-auditory health effects were emailed a short brief of the report aims and asked to send potential papers.

Inclusion criteria were that studies had to: a) be conducted in Europe, b) quantify noise exposure in decibels, and c) compare health effects as odds ratios or relative risks. Potentially vulnerable groups were defined as/based on:

- Individuals with pre-existing disease
- Vulnerable ages – in particular the elderly
- Sex/gender
- Lifestyle and behavioural factors
- Genetic factors
- Situational factors - socioeconomic status and work

The candidate studies were compiled in an Endnote database, and the results of each publication (main paper and supplementary files) were scanned for relevance. Specifically, results stratified by one of the vulnerability themes were sought. For example, results comparing health effects in those with vs. without preexisting disease, men vs. women (most often available as binary biological sex rather than gender), younger vs. older adults, and by lifestyle factors or socioeconomic status (SES) gradients. Data were extracted into an excel spreadsheet under the headings: citation, title, theme, outcome, exposure, study population/design, with the annotated result including reference to table/figure. There was no *a priori* set of outcomes, as the goal was to be as inclusive as possible. In this report, we focus on environmental noise from road, rail, and aircraft, in line with the findings of the "Environmental Noise in Europe" report (EEA, 2025). However, we acknowledge that vulnerabilities and health issues can also arise from noise generated by other sources, such as workplace noise, domestic activities, noise from neighbours or recreational venues, wind turbine noise, and military activities.

2.3 Summary of finding

The results of the review are summarised in the text and in tables. In the tables "Key Findings" column, the relevance of difference between groups is signified by:

- (+) clear difference between groups, statistically significant
- (~) indication of some difference between groups, not statistically significant
- (0) no difference between groups

Noteworthy, our review is based on relative effect measures. Focussing on relative risk (RR) as a primary effect measure has one key implication in terms of vulnerability — even if the RR is the same between groups, it would mean a higher vulnerability for people with high baseline risk (section 2.4).

2.4 Methodological considerations for the analysis – relative risks versus absolute risks

Relative risk and absolute risk are two measures to express the likelihood of an event (e.g. developing a disease) in relation to an exposure such as noise. These two measures, however, convey very different kinds of information. Relative risk, most often used in the types of epidemiological studies considered here, compares the risk of an event between two groups such as for an exposed group vs. a non-exposed or reference group. The relative risk is therefore expressed as a ratio and indicates how much more or less likely the event is in the exposed vs. the unexposed group. The relative risk is

particularly useful for evaluating the strength of an association and suited to research and public health but can be more difficult to use in lay communications.

The absolute risk, on the other hand, informs about the actual probability or chance of an event occurring in a group or individual. The absolute risk is obtained from the relative risk by accounting for the baseline disease risk of the corresponding individual or population group. The absolute risk is expressed as a percentage or rate and provides information about how likely someone is to experience the event. It is useful for understanding individual risk for those within the relevant risk group. To calculate absolute risk for a specific population would require additional effort to derive baseline health data, which in most cases would not be available and could only be estimated (and was not done within this report).

The fact that relative and absolute risk convey two different kinds of information is, for instance, demonstrated in a study by Vienneau et al. (2022) on the association between source specific transportation noise and CVD mortality in Switzerland. For the example from road traffic noise, the study reported higher relative risk for younger compared to older adults which may not be intuitive. However, when the baseline risk for these groups was considered, the story changed. In fact, the study demonstrated that the absolute risk is in fact substantially higher for the older vs. younger adults, which is expected because the overall risk of CVD increases with age. Where we see a large difference in baseline risk across groups, a very different take home message is apparent depending on how the risk is expressed.

3 Summary of the evidence on noise effects in susceptible groups

This section summarises the specific scientific studies and evidence investigating noise effects in vulnerable groups. Chapters 3.1 to 3.6 focus on aspects of susceptibility, while chapter 4 addresses situational factors with an emphasis on socioeconomic status.

Some studies explore more than one vulnerability or potential effect modifier (e.g. socioeconomic status and gender) thus are reported in more than one subsection of chapter 3. When first introduced, the study details (e.g., geographic location, population, study design) are briefly described in the text and entered in the summary table. On next appearance in a subsequent subsection of the text, the study description is brief with reference to the section where it is first introduced. In all instances, the study details are entered into the relevant summary table.

3.1 Individuals with pre-existing disease

Evidence to date suggests that having certain health preconditions that may exacerbate the effects of noise. These broadly include people with cardiometabolic disease, mental health problems, sleep disturbance and hearing impairment and are detailed in the sections below. We have identified two types of studies (Table 3.1). First, some studies have been conducted exclusively in specific vulnerable groups like risk for cardiovascular diseases in relation to noise exposure in patients that have previously experienced an acute coronary syndrome. In such studies, vulnerability is typically not directly addressed but conclusions can be drawn by comparing the exposure-response association with other, population-based, studies addressing the same outcome. Second, population-based studies have conducted stratifications and/or interaction analyses to explore whether the association between noise exposure and outcome of interest is stronger in people with pre-existing diseases. In this case, indications for vulnerability can be directly derived from the study results.

Table 3.1 Summary table of studies on individuals with pre-existing disease

Citation	Study area	Population / study design	Exposure	Outcome	Key finding
People with cardiometabolic disease					
Olbrich et al. (2023)	Frankfurt, Germany	Cohort of over 700 patients with preexisting acute coronary heart disease residing around Frankfurt airport, followed on average for 42 months (from 1 to 80 months)	Aircraft, road, railway (Lden)	Recurrent non-fatal coronary event (myocardial infarction (MI), stroke, bypass surgery or stent implantation) and all-cause mortality	Aircraft: **HR for recurrence**: 1.24 (0.97, 1.58). HR for recurrence and all-cause mortality combined: 1.31 (1.03, 1.66). Road: HR for combined outcome: 1.040 (0.907, 1.193) Railway: **HR for combined outcome**: 1.032 (0.899, 1.185) All per 10 dB Lden.
Cole-Hunter et al. (2022)	Denmark	Danish Nurse Cohort, on 24,994 female nurses aged 44+ years at 1993/1999 recruitment. Longitudinal analysis with mean follow-up of 17.4 years	Road traffic noise (Lden) with residential history calculated as 5-year and 23-year means	All-cause mortality	(~) **HR for pre-existing MI, yes:** 1.39 (1.04, 1.87) vs. **no:** 1.07 (1.01, 1.13); p-int = 0.0766. (0) No difference between those with vs. without **hypertension** (1.06 [0.95, 1.17] vs. 1.08 [1.02, 1.14]; p-int = 0.7379) or **diabetes** (1.18 [0.89, 1.55] vs. 1.07 [1.02, 1.13]; p-int = 0.5068). Per 10 dB Lden.

Citation	Study area	Population / study design	Exposure	Outcome	Key finding
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Stroke incidence, CVD and all-cause mortality	(~) **HR no comorbidity**: 1.16 (1.05, 1.30) vs. **HR comorbidity**: 1.04 (0.97, 1.11); p-int = 0.085. (0) No difference for **CVD or all-cause mortality**; p-int > 0.3. Per 10 dB Lden.
Tonne et al. (2016)	Greater London, United Kingdom	Patients from the Myocardial Ischaemia National Audit Project database living in Greater London (n = 18,138) were followed for death or readmission for MI	Road traffic noise (LAeq16)	Hospital readmission for MI among survivors of hospital admission for MI	HR for all-cause mortality: 1.02 (0.99, 1.06). HR for all-cause mortality or MI readmission: 1.02 (0.99, 1.05). Per 5 dB LAeq16.
People with mental health problems					
Bartoskova Polcrova et al. (2025)	Brno, Czech Republic	Cross-sectional population-based study, 2031 adults	Combined road traffic, railway and aircraft noise (Lden) from 2012 strategic noise mapping	Number of depressive symptoms (PHQ-9). Adiposity biomarkers: BMI, % body fat (%BF), waist circumference (WC), and visceral fat area (VFA)	(+) Noise-adiposity association was modified by **depressive symptoms**. Q4 noise and 10+ vs <5 symptoms: **BMI:** 0.305 (0.075, 0.534); p-int = 0.042. (~) **WC:** 0.286 (0.063, 0.059); p-int = 0.104. **%BF:** 0.221 (0.026, 0.416); p-int = 0.131. (0) **VFA:** 0.290 (0.069, 0.510); p-int = 0.259.

Citation	Study area	Population / study design	Exposure	Outcome	Key finding
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) No difference in **global cognitive score** by **depression CES-D** (<18 vs. ≥18), overlapping 95% CIs (exact estimates not given).
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) No difference in **MCI** by CES-D (<18 vs. ≥18), overlapping 95% CIs (exact estimates not given).
Halonen et al. (2014)	Finland	Cross-sectional analysis in cohort of public sector employees, including >4000 men and women (mean age 50, range 21-76 years)	Road traffic noise (Lden), from 10m maps	Self-rated health and register-based use of antidepressants, anxiolytics, and hypnotics. Potentially vulnerable individuals (that may be noise sensitive) identified using high trait anxiety scores	(~) Poor self-rated health in subset of men with trait anxiety score: For exposure >60 dB vs. <=45 dB, OR high anxiety: 2.23 (1.28, 3.89) OR for low anxiety: 1.20 (0.75, 1.99).
People with sleep disturbance					

Citation	Study area	Population / study design	Exposure	Outcome	Key finding
Gong et al. (2024)	Living in Local Authority Districts whole or partly covered by noise contours of four major airports (London Heathrow, London Gatwick, Birmingham and Manchester), United Kingdom	UK Biobank cohort study, participants 40-69 years at recruitment (2006-2010). Cross-sectional (n>18000) and repeated cross-sectional design (n>84000), depending on outcome	Aircraft noise contours (Lnight) assigned to postcode and categorised in 5 dB steps	Objective and subjective sleep disturbance, defined separately by actimetric data (cross-sectional) and self-report (repeated cross-sectional)	(~) Those with diabetes, dementia or sleep disorder (but not with hypertension, BMI>median or mental health problems) are more impacted than the total sample.
People with hearing impairments					
Wu et al. (2024)	Sweden	Swedish National study on Aging and Care in Kungsholmen (SNAC-K), including 2594 dementia-free participants aged 60+ years followed up to 16 years	Road traffic, railway and aircraft noise (Lden) most exposed façade, accounting for address history	GCS (global cognition score) and CIND (cognitive impairment, no dementia)	(0) No difference in **GCS** nor **CIND** for any noise source, in models stratified by **hearing loss (yes vs. no)** with p-int > 0.21.

In Key findings:
‘p-int’ refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups
Note: not all findings in this chapter are direct comparisons, thus symbols (+), (~), (0) are only added where relevant

3.1.1 People with cardiometabolic disease

Olbrich et al. (2023) investigated whether aircraft noise exposure at home is related to recurrences of cardiovascular events in a cohort of over 700 patients with preexisting acute coronary heart disease residing in the area around Frankfurt airport. The study explored both recurrent non-fatal coronary events (myocardial infarction (MI), stroke, bypass surgery or stent implantation) and all-cause mortality, following the patients on average 42 months (from 1 to 80 months). The risk for recurrence was 24% (1.24 [95%-CI: 0.97, 1.58]) per 10 dB increase in Lden and was higher at 31% when combining recurrence and all-cause mortality (1.31 [95%-CI: 1.03, 1.66]). The exposure-response in Olbrich et al. (2023), for example, is substantially elevated compared to the findings of previous large, general population-based studies in relation to cardiovascular deaths or MI.

Mortality was studied by Cole-Hunter et al. (2022) in the large Danish Nurses cohort including 24,994 female nurses aged 44+ years at recruitment (in 1993/1999) and followed for a mean of 17.4 years. Outcomes included all-cause and cause-specific mortality and potential differences in effects were studied comparing participants with vs. without preexisting hypertension, diabetes or MI based on self-report, medication or hospitalisation. Effect modification was also explored by age and lifestyle. Road traffic noise (Lden) was modelled within 5-year and 23-year windows. The models were adjusted for personal, behavioural factors and SES, with the main model additionally adjusted for $PM_{2.5}$. Road traffic noise was associated with all-cause mortality, with a stronger association for the longer exposure period (1.08 [1.02, 1.13] per 10 dB 23-year mean Lden). There was no difference in association for those with vs. without hypertension (1.06 [0.95, 1.17] vs. 1.08 [1.02, 1.14]; p-int = 0.7379) or diabetes (1.18 [0.89, 1.55] vs. 1.07 [1.02, 1.13]; p-int = 0.5139). Having previous MI, however, indicatively increased the risk of all-cause mortality in relation to road traffic noise exposure compared to the group with no history of MI (1.39 [1.04, 1.87] vs. 1.07 [1.01, 1.13]; p-int = 0.0766).

A more recent UK Biobank study by Hao et al. (2022) included 342,566 participants 40-69 years at recruitment (2006-2010). These individuals were free of CVD at baseline and followed for a median of 9 years. This study investigated incident CVD including stroke, ischemic stroke, IHD and AMI, as well as CVD and all-cause mortality. The authors investigated effect modification by age, sex, family history of CVD and socioeconomic status. Of interest here, they also explored potential effect modification by the presence vs. absence of comorbidity defined as hypertension, high cholesterol or diabetes. The main analysis showed only showed a borderline significant association for road traffic noise and incident stroke that attenuated after adjusting for $PM_{2.5}$. The analysis stratified by comorbidity indicated this effect was mainly in those without comorbidity, though the difference between groups was not statistically significant (HR no comorbidity: 1.16 [1.05, 1.30] vs. HR comorbidity: 1.04 [0.97, 1.11] per 10 dB Lden; p-int = 0.085). There was no difference in the association between road traffic noise and CVD or all-cause mortality with p-int > 0.3. An earlier study of 18,138 patients from the Myocardial Ischaemia National Audit Project database resident in Greater London also did not find elevated risks for death nor death or MI readmission in relation to road traffic noise (HR = 1.02 [95%-CI: 0.99, 1.06] and 1.02 [0.99, 1.05] per 5 dB increase in daytime noise) (Tonne et al., 2016).

3.1.2 People with mental health problems

Several studies have looked at association between noise and metabolic biomarkers with a special focus on individuals with preexisting mental health issues. The first is a cross-sectional population-based study of 2031 adults in Brno, Czech Republic that investigated whether depression – here considered a preexisting disease – modified the association between noise and adiposity (Bartoskova Polcrova et al., 2025). Exposure was determined from strategic noise mapping, for combined road traffic noise, railway and aircraft noise. Amongst participants within the highest noise quartile (>56 dB Lden), associations for all four biomarkers were strongest in those with 10 or more depressive symptoms compared to those with less than 5 (BMI: 0.305 (0.075, 0.534); waist circumference: 0.286

(0.063, 0.059); body fat percentage: 0.221 (0.026, 0.416); visceral fat area: 0.290 (0.069, 0.510). However, only the interaction for BMI was statistically significant (p = 0.042).

Within the Finnish Public Sector Study, which included employees from ten towns and six district hospitals in Finland, Halonen et al. (2014) conducted a cross-sectional analysis to explore the association between road traffic noise and self-rated health and register-based use of antidepressants, anxiolytics, and hypnotics. In total this analysis was based on >4000 men and women (mean age 50, range 21-76 years). Potentially vulnerable individuals were also identified using high trait anxiety scores, which the authors speculate may be indicative of noise sensitivity. Models to evaluate potential effect modification in terms of sex and, of relevance here, trait anxiety score which we use as a proxy for preexisting disease. For road traffic noise exposure >60 dB vs. <=45 dB and poor self-rated health, the OR for men with a high anxiety trait score was elevated at 2.23 (1.28, 3.89) compared to 1.20 (0.75, 1.99) for those with a low anxiety trait score. A similar stratified analysis by trait anxiety score was not conducted for women nor for psychotropic medication use as the overall associations for these were null.

In contrast, two studies in Germany within the same study population did not find that depression modified noise effects on cognition in adults. Within the Heinz Nixdorf Recall study (2006–2008 second evaluation), a population-based study in the Ruhr area of Germany, cognitive performance was evaluated in 4086 participants (mean age 64 years) and examined in relation to traffic noise (Tzivian et al., 2016a). Cognitive performance was evaluated with a battery of tests including on verbal fluency, the labryinth test, immediate recall, delayed recall, global cognitive score, the clock drawing test. Exposure to road traffic noise at the most exposed façade was used as continuous variable with a threshold at 60 dB for Lden and 55 dB for Lnight. Overall, road traffic noise was only associated with reduced global cognitive score, however this attenuated to null on adjustment for air pollution. The study included an extensive exploration of potential effect modification, including stratified models for age, sex, lifestyle, SES, genetic predisposition and pre-existing disease. For the latter, depressive symptoms were evaluated using the CES-D scale; overlapping 95% confidence intervals indicated no difference in global cognition score in those with CES-D <18 vs. ≥18 (exact estimates not given). Tzivian et al. (2016b) also investigated the cross-sectional association between road traffic noise exposure and mild cognitive impairment in this cohort. In the full population, mild cognitive impairment was associated with noise above the threshold. Similar to their other study, the authors included a suite of analysis on effect modification, including pre-existing disease. For depressing as a pre-existing disease, they again found no difference in mild cognitive impairment between those without (CES-D <18) vs. (CES-D ≥18) with depressive symptoms (exact estimates not given).

3.1.3 People with sleep disturbance

A UK Biobank study including individuals living in the Local Authority Districts, whole or partly covered by aircraft noise contours from four major airports, looked into the association between nighttime aircraft noise exposure and a range of objective and subjective measures of sleep disturbance (Gong et al., 2024). The study included participants 40-69 years at recruitment (2006-2010) and used a cross-sectional (n > 18000) design for the objective actimetric data analyses and repeated cross-sectional design (n > 84000) for the subjective outcomes based on self-report. The authors included stratified analyses to investigate a range of vulnerabilities, including pre-existing disease along with age, sex and indicators of socio-economic status. Regarding pre-existing disease, Gong et al. (2024) found that individuals with diabetes, dementia and sleep disorder showed stronger associations between Lnight and sleep disturbance than the total population included in the study, while there was no difference for those with hypertension, BMI above the median or mental health problems.

3.1.4 People with hearing impairments

Acute or chronic exposure to high levels of noise impairs the hearing. Numerous studies have established an association between hearing loss and noise exposure, mainly in relation to noise at the workplace (Themann and Masterson, 2019). On the other hand, some studies have shown that hearing-impaired individuals have more difficulty understanding speech in noisy environments, such as when in public transportation or while operating vehicles. Even with hearing aids, speech discrimination when there is transportation noise remains poor, and hearing aids may amplify harmful noise, potentially worsening hearing damage (Casali and Gerges, 2006; Lee et al., 1981). This can impact job performance, safety, and social interactions (Casali and Gerges, 2006; Lee et al., 1981). Further, it has been suggested that people with hearing impairment may be more annoyed and distressed from chronic noise exposure, compounding difficulties in daily life, potentially putting them at higher risk to develop stress related disease.

One specific study that explored effect modification by hearing loss is that by Wu et al. (2024) which used the Swedish National study on Aging and Care in Kungsholmen (SNAC-K) to investigation transportation noise in relation to cognitive function in older adults. The study included 2594 dementia-free participants aged 60+ years who were followed up to 16 years. Road traffic, railway and aircraft noise at the maximum exposed facade were calculated as time-weighted average exposures according to address history. Outcomes included a global cognition score and cognitive impairment, no dementia (CIND), both assessed with standard tests. The authors explored effect modification by age, sex, lifestyle and – relevant to this section – hearing loss. None of the transportation noise sources were associated with decline in global cognition score regardless of hearing loss status, with p-int = 0.288, 0.215, and 0.298 respectively for road traffic, aircraft and railway noise. CIND incidence was also not significantly different between those with vs. without hearing loss, with p=interactions of 0.838, 0.567 and 0.404 respectively for road traffic, aircraft and railway noise.

3.2 Vulnerable ages – in particular the elderly

This section focuses on vulnerable ages in adulthood (Table 3.2). As highlighted in section 2.4, older age is such a strong risk factor for disease, leading to high absolute risks, with old people almost by definition more vulnerable for most diseases including cardiometabolic disease and death. Thus, most studies relevant to this chapter are on the elderly, though reproductive aged adults in relation to reproductive outcomes are also considered. Children are only briefly mentioned in the context of cognition, as this topic is presented elsewhere (EEA, 2024; Engelmann et al., 2025).

Table 3.2 Summary table of studies on vulnerable ages – in particular the elderly

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Cardiometabolic disease					
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Stroke incidence	(0) No difference. **Incident stroke, HR <60 years**: 1.10 (1.00, 1.21) and **HR ≥60**: 1.05 (0.98, 1.13); p-int = 0.766. Both per 10 dB Lden.
Pyko et al. (2019)	Stockholm County, Sweden	Longitudinal CEANS cohort including 20,012 individuals from 4 subcohorts, aged 35-104 years (mean 60) at entry	Road traffic, railway and aircraft noise (Lden) 1-5 years prior at most exposed façade accounting for residential history	IHD incidence	(0) No difference in HR for **age above vs. below median**; p-int = 0.17 (exact HR not provided).
Halonen et al. (2015)	Greater London, United Kingdom	8.6 mil inhabitants, small-area study	Road traffic noise (LAeq16 and Lnight) in steps of 5 dB	CVD hospital admissions, for all CVD, IHD and stroke	(0) No difference. RR for stroke in adults (≥25 years): 1.05 (1.02, 1.09), RR for stroke in elderly (≥ 75 years): 1.09 (1.04, 1.14). Both in areas exposed to >60 vs. <55 dB LAeq16.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Sørensen et al. (2012)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2006 (mean 9.8 years)	Road traffic noise (Lden)	MI incidence	(~) **IRR below 65 years:** 1.06 (0.95, 1.18), **IRR 65+ years**: 1.19 (1.06, 1.34); p-int = 0.10 Per 10 dB Lden.
Selander et al. (2009)	Stockholm County, Sweden	Case-control study conducted 1992-1994, in the Stockholm Heart Epidemiology Program, including 3666 participants (1571 cases; 2095 controls). Included adults between 45–70 years old with no history of MI.	Road traffic noise (LAeq,24 above 50 dBA vs. below), accounting for address history	Incident fatal and non-fatal myocardial infarction (MI)	(0) No difference or trend in risk by age (5-year age bands). All associations were null, with overlapping 95% CIs (exact ORs not provided).
Self-reported health status					
Dzhambov et al. (2023)	Sofia, Bulgaria	Cross-sectional population-based survey of 917 adults responding to questionnaire on poor self-rated health.	Road traffic, railway and aircraft noise (Lden) from 10m strategic noise maps	Poor self-rated health (PSRH). Obtained from a single question "In general, how would you rate your health?", with no specific time frame reference. Responses were on a 5-pt scale.	(0) No evidence of effect modification by age.
Mutz et al. (2021)	United Kingdom	UK Biobank, including 307,378 adults. Cross-sectional analysis	Road traffic noise (Lden)	Health status (from algorithm), preexisting disease, self-reported health	(0) No difference in the null association by age (below vs. above 65 years) for any of the outcomes.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Klompmaker et al. (2019)	Netherlands	Cross-sectional study, Public Health Monitor 2012 survey including 354,827 adults (oversampled ≥65 years)	Road traffic and railway noise (Lden) from 10m maps	Self-perceived general health (SGH)	(0) No difference. **Railway noise OR <65 years**: 1.02 (0.98, 1.06), **OR ≥65 years**: 1.03 (1.00, 1.06). Per 8.9 dB.
Sleep disturbance					
Gong et al. (2024)	Living in Local Authority Districts whole or partly covered by noise contours of four major airports (London Heathrow, London Gatwick, Birmingham and Manchester), United Kingdom	UK Biobank cohort study, participants 40-69 years at recruitment (2006-2010). Cross-sectional (n>18000) and repeated cross-sectional design (n>84000), depending on outcome	Aircraft noise contours (Lnight) assigned to postcode and categorised in 5 dB steps	Objective and subjective sleep disturbance, defined separately by actimetric data (cross-sectional) and self-report (repeated cross-sectional)	(~) Generally little difference in associations by age except for the over 55 year-olds showing higher sleep duration.
Infertility					
Sørensen et al. (2024)	Denmark	Nationwide prospective cohort of 0.9 mil women and men (aged 30-34) followed from 2000 to 2017	Road traffic noise (Lden) modelled at maximum exposed façade	Incident infertility	(+) Higher risk of infertility in relation to RTN at max exposed facade in older (37-45y) vs. younger (30-36.9y) adults, with **HR older men**: 1.06 (1.02, 1.10), **HR younger men:** 0.94 (0.91, 0.96), **HR older women:** 1.13 (1.10, 1.17), **HR younger women:** 0.98 (0.96, 1.01). Per 10 dB Lden.
Cognition					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Wu et al. (2024)	Sweden	Swedish National study on Aging and Care in Kungsholmen (SNAC-K), including 2594 dementia-free participants aged 60+ years followed up to 16 years	Road traffic, railway and aircraft noise (Lden) most exposed façade, accounting for address history	GCS (global cognition score) and CIND (cognitive impairment, no dementia)	(~) Little difference in GCS nor CIND for any noise source, in models stratified by young-old vs. old-old; p-int > 0.093.
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) No difference in global cognitive score by age (<65 vs. ≥65 years), overlapping 95% CIs (exact estimates not given).
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) No difference in MCI by age (<65 vs. ≥65 years), overlapping 95% CIs (exact estimates not given).
Cancer					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Sørensen et al. (2021)	Denmark	Administrative cohort of 1.8 million cancer-free women at baseline, followed for up to 16 years	Road traffic noise (Lden) at most and least exposed façade accounting for address history	Breast cancer	(0) No evidence of effect modification by age of diagnosis (exact IRRs not provided).
Mortality					
Sørensen et al. (2023)	Denmark	Nation-wide cohort including 2.6 million Danes aged 50 years and older, followed on average for 11.7 years (600,492 natural deaths)	Road traffic and railway noise (Lden) at most (LdenMax) and least (LdenMin) exposed facades considering residential history	Natural cause, cardiovascular, respiratory and cancer mortality	(~) **Road traffic noise and natural mortality HR <70 years:** 1.05 (1.05, 1.06), **HR 70-80 years:** 1.08 (1.08, 1.09), and **HR ≥ 80 years:** 1.13 (1.13, 1.14) per 10 dB LdenMax. Same patterns found for CVD and respiratory mortality, but no effect modification for cancer mortality. (0) No apparent pattern with LdenMin.
Cole-Hunter et al. (2022)	Denmark	Danish Nurse Cohort, on 24,994 female nurses aged 44+ years at 1993/1999 recruitment. Longitudinal analysis with mean follow-up of 17.4 years.	Road traffic noise (Lden) with residential history, calculated Lden as 5-year and 23-year means.	All-cause mortality	(0) No difference. For all-cause mortality, **HR for <65 years**: 1.06 (0.99, 1.13), **HR for ≥65 years**: 1.08 (1.00, 1.17); p-int = 0.6148. Per 10 dB Lden 23-year mean.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342, 566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	CVD and all-cause mortality	(0) No difference. **CVD mortality, HR <60 years:** 1.02 (0.89, 1.18) and **HR ≥60**: 1.17 (1.07, 1.29); p-int = 0.456. **All-cause mortality (HR <60 years:** 1.09 (1.03, 1.16) and **HR ≥60:** 1.07 (1.03, 1.12); p-int = 0.339). Per 10 dB Lden.
Vienneau et al. (2022)	Switzerland	Cohort, SNC with 4.1 mil adults over 30 years followed for up to 15 years.	Road traffic, railway and aircraft noise (Lden)	All CVD, blood pressure related, ischemic heart disease (IHD), myocardial infarction (MI), heart failure (HF), stroke, haemorrhagic stroke (HS), ischemic stroke (IS)	(+) HR were higher for younger (30-64 years) vs. older (>65 years) adults for **road traffic noise and CVD** (e.g. 1.086 (1.073, 1.099) 30-65 yr, 1.027 (1.020, 1.034) 65-79 yr, 1.008 (1.000, 1.016) 80+ yr per 10 dB Lden; p-trend <0.0001), **IHD, MI, stroke and HS mortality** (p-trend <=0.002). (+) Same pattern for railway noise and all CVD and IHD mortality and for aircraft noise and all CVD, IHD and MI mortality.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Klompmaker et al. (2021)	Netherlands	10.5 mil adults ≥ 30 years, followed from 1.1.2013 to 31.12.2018	Road traffic noise (Lden)	Natural and cause-specific mortality	(+) Higher HR in younger (<65 yr) vs. older (>=65 yr) adults for **natural** (~1.03), **circulatory disease** (~1.03), **respiratory disease** (~1.05), **lung cancer** (~1.06) and **COPD** (~1.05) **mortality**. (0) Overlapping HR for IHD, neurodegenerative disease, cerebrovascular disease and dementia mortality.
Halonen et al. (2015)	Greater London, United Kingdom	8.6 mil inhabitants, small-area study	Road traffic noise (LAeq16 and Lnight) in steps of 5 dB	All CVD, IHD and stroke and all-cause mortality	(0) No difference. RR for **all-cause mortality** in **adults ≥25 years vs. ≥ 75 years** were similar, with 1.03 (1.01, 1.05) in areas with 55-60 vs. <55 dB LAeq16.

In Key findings:
‘p-int’ refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups

3.2.1 Cardiometabolic disease

Several studies on the association between noise and CVD have included subset analysis to explore potential differences by age and sex, with most finding no differences. Selander et al. (2009) conducted a case-control study between 1992-1994 that included 3666 participants (1571 cases; 2095 controls) in Stockholm County to study road traffic noise in relation to myocardial infarction (MI). The study included men and women between 45–70 years old with no history of MI. There was no difference or clear trend in risk of MI by age, with participants grouped into 5-year bands. All associations were null, and all group confidence intervals were overlapping (exact OR values not provided). The authors also explored effect modification by sex.

Cardiovascular disease incidence in relation to source-specific transportation noise was extensively studied in the CEANS cohort in Stockholm County (Pyko et al., 2019). The cohort included 20,012 individuals aged 35 and older compiled from four sub-cohorts. Road traffic, railway and aircraft noise Lden, 1-5 years prior to entry, were assigned based on noise levels at the most exposed residential façade. Outcomes included IHD, MI, stroke and ischemic stroke incidence, as well as IHD and stroke mortality. The study found no overall association between the noise exposures and CVD incidence, but also looked into effect modification by age, sex and education for IHD incidence. Regarding age, the stratified analyses showed no difference in HR for age above vs. below median (p-int = 0.17, exact HR not provided).

The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342, 566 participants 40-69 years at recruitment (2006-2010) who were free of CVD at baseline. Incident CVD outcomes included stroke, ischemic stroke, IHD and AMI. The main analysis showed only showed a borderline significant association for road traffic noise and incident stroke that attenuated after adjusting for $PM_{2.5}$. When looking at difference by age, the authors reported slightly higher HR for incident stroke in younger vs. older adults using 60 years as the cut-point. It should be noted, however, that the associations were not significant (HR <60 years: 1.10 [1.00, 1.21] and HR ≥60: 1.05 [0.98, 1.13] per 10 dB Lden, p-int = 0.766). A small-area study in Greater London of 8.6 million inhabitants on CVD hospital admissions found indications of increased risk in the elderly defined as over 75 years compared to all adults over 25 years, particularly for stroke. Though not significantly different, the RR for stroke was 1.09 (1.04, 1.14) for the elderly vs. 1.05 (1.02, 1.09) for adults, each comparing risk for those living in areas exposed to >60 vs. <55 dB daytime noise (Halonen et al., 2015).

Sørensen et al. (2012) included over 57000 adults between the ages of 50 and 64 years at enrolment and followed them for almost 10 years to study the relationship between road traffic noise exposure and incidence of myocardial infarction (MI). It investigated effect modification by age as well as sex and socioeconomic status. Regarding age, the study found greater risk of MI in those over vs. under 65 years of age. Though the risk amongst the two groups was not significantly different, it amounted to 19% increased risk [1.19 (1.06, 1.34)] per 10 dB vs. 6% increased risk [1.06 (0.95, 1.18)] (Sørensen et al., 2012).

3.2.2 Self-reported health status

Several studies have looked at age as a potential modifier of associations between transportation noise and self-reported health status, all showing no differences. One such study is a cross-sectional population-based survey in Sofia, Bulgaria that included over 900 adults asked to self-rate their general health (Dzhambov et al., 2023). Responses were then explored in relation to transportation noise exposures, stratified by age, sex and socioeconomic status thus applicable to several of the potential vulnerable groups of interest. Further, the models accounted for co-exposures including greenspace and air pollution. Regarding age, there was no evidence of effect modification on poor self-rated health

in relation to noise exposure. However, the age range of participants was 18 to 65 years (mean of 45 years), thus the elderly were not included in the survey.

A similar yet much larger study in the Netherlands including 354,827 adults, found that self-perceived general health was weakly associated with railway noise but not road traffic noise. In the analysis stratified by age, it found that the association for railway noise was mainly in the elderly though the difference between groups was not significant (odds ratio 1.03 [1.00, 1.06] in those 65+ vs. 1.02 [0.98, 1.06] in <65 years of age group, per 8.9 dB railway noise) (Klompmaker et al., 2019).

Finally, Mutz et al. (2021) conducted a large study of 307,378 adults within the UK Biobank to explore health in relation to a range of socio-environmental factors including road traffic noise. The main outcome was health status, defined using an algorithm and collected self-reported data on 81 cancers and 443 non-cancer illnesses, past and current. Two secondary outcomes were also explored: preexisting disease, was defined using the question "Do you have any long-standing illnesses, disability of infirmity?" while perceived health was determined based on the question "In general how would you rate your overall health?" No overall association was found between road traffic noise (Lden) and self-reported health status. The stratified results also showed no difference by age (below vs. above 65 years) for any of the studied outcomes.

3.2.3 Sleep disturbance

The UK Biobank study on aircraft noise and sleep disturbance by Gong et al. (2024) and described in section 3.1.3 also looked at difference in objective and subjective sleep measure by age. In general, the authors found little difference in associations by age except for those over 55 years where the study found higher sleep duration in this group.

3.2.4 Infertility

One prospective nationwide cohort from Denmark investigated the relationship between road traffic noise and incident infertility (Sørensen et al., 2024). It included all women and men between 30 and 45 years old who were cohabiting or married, with less than 2 children, and living in the country between 2000 and 2017 (n= 377,850 women; 526,056 men). Incident infertility was determined by linkage to the Danish National Patient Registry. Road traffic noise was estimated at the most and least exposed facade, using the address history. The authors investigated associations in younger vs. older adults of reproductive age, and by indicators of socioeconomic status. The study found higher risk of incident infertility in relation to road traffic noise at the maximum exposed facade in the older (37-45y) vs. younger (30-36.9y) age category, with HRs of: 1.06 (1.02, 1.11) per 10.2 dB Lden older men; 0.93 (0.91, 0.96) younger men; 1.14 (1.10, 1.18) older women; 0.98 (0.96, 1.01) younger women. The associations were stronger in older women for subtypes of infertility including anovulation and tubal factor, and in both men and women who had no silent facade (i.e. minimal difference in road traffic noise level at the maximum vs. minimum exposed façade).

3.2.5 Cognition

Cognition and learning are primarily outcomes related to children/adolescents with these ages particularly vulnerable because of learning and being in this developmental phase. The effects of transportation noise on children's learning and cognition have thus been issues of concern for some time, with research tending to focus on transportation noise exposure on school performance. The RANCH study is one such example, including over 2000 8-9 year old children in schools near London Heathrow, Amsterdam Schiphol and Madrid Barajas airports, that found aircraft noise exposure was related to poorer reading comprehension (Stansfeld et al., 2005). As such, cognitive impairment in general was addressed in the ENG (WHO, 2018) as a critical health outcome. The supporting review by Clark and Paunovic (2018), however, identified that all papers on relevant noise and cognition published up to June 2015 were on children. A more recent review found that children living or going

to schools in noisy areas tended to have lower reading comprehension and more behavioural challenges, with conservative estimates of children impacted being over 500,000 and almost 60,000, respectively (Engelmann et al., 2025). Cognition in children is addressed in a separate review (EEA, 2024; Engelmann et al., 2025), thus is not elaborated further here.

Compared to children, less is known about how transportation noise impacts cognition in the elderly, an issue of importance given the aging population in Europe and beyond. As summarized in Engelmann et al. (2024) several reviews have been published since the ENG (WHO, 2018) and Clark and Paunovic (2018) reviews, that focus on or include evidence for cognitive impairment in adults. Based on three studies, a review by Thompson et al. (2022) reported increased odds of cognitive impairment in adults 45 years and older exposed to higher noise levels. Several studies have specifically looked at whether age modifies the effects of noise on cognition in adults.

As described in section 3.1.4, Wu et al. (2024) used the Swedish National study on Aging and Care in Kungsholmen (SNAC-K) to study transportation noise in relation to cognitive function in older adults. They included and followed 2594 dementia-free participants (aged 60+ years) for to 16 years and studied a global cognition score and cognitive impairment, no dementia (CIND), both assessed with standard tests. Age groups were defined as young-old (age ≤78 years) vs. old-old (age >78 years). None of the transportation noise sources were associated with decline in global cognition score for either age group, with p-int = 0.888, 0.758, and 0.527 respectively for road traffic, aircraft and railway noise. CIND incidence was also not significantly different between the young-old and old-old groups, with p=int = 0.093, 0.354 and 0.815 respectively for road traffic, aircraft and railway noise.

Two cross-sectional analyses in the Heinz Nixdorf Recall study (2006–2008), a population-based study in the Ruhr area of Germany described in section 3.1.2, were also conducted to study cognition in adults. The first evaluated cognitive performance in relation to traffic noise in 4086 participants with a suite of six tests (Tzivian et al., 2016a). In the full study population, an association was only found between road traffic noise Lden above the 60 dB threshold and global cognitive score. There was no difference in effect by age, as determined by the overlapping 95% confidence intervals in models stratified by age <65 vs. ≥65 years (exact estimates not given). Within the same study population, Tzivian et al. (2016b) explored mild cognitive impairment. A significant association was found for both Lden and Lnight above the thresholds in the full study population. There was, however, no difference in effect by age, as determined by the overlapping 95% confidence intervals in models stratified by age <65 vs. ≥65 years (exact estimates not given).

3.2.6 Cancer

Using an administrative record linkage to capture all women in Denmark, Sørensen et al. (2021) constructed and retained a cohort of 1.8 million eligible and cancer-free women at baseline. They studied road traffic and railway noise, modelled at both the maximum and minimum exposed facades per dwelling, in relation to breast cancer incidence. In this large study, individuals were followed for a up to 16 years. Overall, the risk for breast cancer was increased in relation to road traffic noise regardless of façade estimate used for exposure assessment. The IRRs were 1.012 (1.002, 1.022) for the maximum exposed façade, and higher for the minimum exposed façade at 1.032 (1.019, 1.046) per 10 dB road traffic noise. There was no clear trend, however, in effects by age at diagnoses defined in three groups which were <50 years, 50-55 years and ≥55 years (graphical results only). The authors also studied potential effect modification by socioeconomic status.

3.2.7 Mortality

Several large studies investigating natural and cause-specific mortality in relation to transportation noise have included analyses on effect modification by age. As a whole, the findings are mixed and depend on exposure source and outcome. One of the first studies the small-area study in Greater

London, UK study by Halonen et al. (2015), that included 8.6 million inhabitants that considered CVD (all, IHD and stroke) mortality and all-cause mortality in relation to road traffic noise. The RR for all-cause mortality in adults ≥25 years vs. ≥ 75 years were similar, with 1.03 (1.01, 1.05) in areas with 55-60 vs. <55 dB LAeq16. Risk was also elevated, at 4%, in the areas with >60 dB LAeq16, though with slightly wider 95% CIs. Small increased risks were also noted in relation to all CVD for the elderly, and both populations and IHD mortality for Laeq16. No associations were reported in relation to Lnight.

Klompmaker et al. (2021) used the Dutch nationwide administrative cohort with 10.5 million adults over 30 years old to study road traffic and railway noise, amongst other exposures, in relation to natural and cause-specific mortality (60 mil person-years, 776,021 natural-cause deaths). Results for effect modification by age for road traffic noise were presented in figures, showing the following patterns. HR for natural-cause (HR~1.03), circulatory disease (~1.03), respiratory disease (~1.08), lung cancer (~1.06) and COPD (~1.05) mortality were higher in younger (<65 yr) compared to older (>=65 yr) adults. For IHD, neurodegenerative disease, cerebrovascular disease and dementia mortality the 95% confidence intervals were overlapping indicating no difference between age groups. For all outcomes, mortality in the older adults was null except for a positive association in relation to lung cancer mortality. However, the authors also note that indirect adjustment was likely insufficient to account for smoking, likely leading to overestimation for lung cancer mortality.

Mortality in relation to road traffic noise was studied by Cole-Hunter et al. (2022) in the Danish Nurses cohort (section 3.1.1). Outcomes included all-cause and cause-specific mortality, with effect modification only presented for the latter. The authors found that the association between road traffic noise and all-cause mortality did not differ by age, with 1.06 (0.99, 1.13) for those less than 65 years vs. 1.08 (1.00, 1.17) for those over 65 years per 10 dB 23-mean Lden (p-int = 0.6148).The UK Biobank study by Hao et al. (2022), described in section 3.1.1, included 342, 566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline. In addition to investigating incident CVD, the authors looked at the relationship between road traffic noise Lden and mortality by age. For CVD mortality, the association with road traffic noise was stronger in the older compared to younger adults but not statistically different (HR <60 years: 1.02 (0.89, 1.18) per 10 dB Lden and HR ≥60: 1.17 (1.07, 1.29), p-int = 0.456). Associations were more similar for all-cause mortality (HR <60 years: 1.09 (1.03, 1.16) per 10 dB Lden and HR ≥60: 1.07 (1.03, 1.12), p-int = 0.339).

Sørensen et al. (2023) report on the associations between road traffic and railway noise, at both the maximum (LdenMax) and maximum (LdenMin) exposed facades, in relation to natural and cause-specific mortality in the nation-wide Danish cohort. The population included 2.6 million adults over 50 years of age, followed for an average of 11.7 years during which time 600,492 died of natural causes. The authors studied effect modification for a number of factors including age. For road traffic noise, natural cause mortality increased age, with HRs of 1.05 (1.05, 1.06) for <70 years, 1.08 (1.08, 1.09) for 70-80 years, and 1.13 (1.13, 1.14) for ≥ 80 years, per 10 dB LdenMax. The same patterns were found for CVD and respiratory mortality, also with overlapping 95% confidence intervals. There was no indication of effect modification by age for cancer mortality, with the HRs around 1.02 per 10 dB LdenMax. The pattern of increasing risk with increasing age was not apparent when using the minimum exposed facade. Effect modification was not explored for railway noise, however it was included as an adjustment in the analyses on road traffic noise. The authors also studied effect modification by sex and by socioeconomic status.

Finally, cause-specific CVD mortality in relation to road traffic, railway and aircraft noise exposure was studied in the Swiss National Cohort, including 4.1 million adults over 30 years of in a longitudinal study with a mean follow-up of 13.4 years (Vienneau et al., 2022). Of the studies on transportation noise and mortality, this was most consistent in its finding that age modifies the associations. Noise was estimated at three time points, and models were mutually adjusted for noise from other sources and

air pollution. Outcomes included all CVD mortality, as well blood-pressure related, IHD, myocardial infraction, heart failure, all stroke, haemorrhagic stroke and ischemic stroke deaths. Effect modification by age and sex was explored, with results for all CVD mortality presented both as relative and absolute risk. The authors found higher HR for younger adults (30-64 years) compared to older (>65 years) for CVD, IHD, myocardial infraction, stroke and haemorrhagic stroke in relation to road traffic noise (p-trend <=0.002). For CVD mortality, the estimates per age group were: 1.086 (1.073, 1.099) for 30-64 year-olds, 1.027 (1.020, 1.034) for 65-79 year-olds, and 1.008 (1.000, 1.016) for 85+ year-olds per 10 dB road traffic noise (p-trend <0.0001). The absolute risk for CVD mortality, however, was as expected higher in the older adults due to higher baseline CVD mortality risk (section 2.4). Similarly, the HRs were higher in younger compared to older adults for all CVD and IHD mortality in relation to railway noise and for all CVD, IHD and myocardial infarction in relation to aircraft noise.

3.3 Sex/Gender

This section focuses on whether there are differences in vulnerable for adults depending on sex or gender (Table 3.3). It should be noted that studies included in this review, many of which are based on use of registry data, tend not to have information on gender thus use biological sex. Another important point is that some health outcomes that may be relevant to noise exposure are mainly applicable and thus studied for one sex, such as breast cancer for women and prostate cancer for men. Here, we only include studies that include both sexes and report the stratified results.

Table 3.3 Summary table of studies on sex/gender

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Cardiometabolic disease					
Bartoskova Polcrova et al. (2025)	Brno, Czech Republic	Cross-sectional population-based study, 2031 adults	Combined road traffic, railway and aircraft noise (Lden) from strategic noise mapping	Adiposity biomarkers: BMI, % body fat (%BF), waist circumference (WC), and visceral fat area (VFA)	(0) Noise-adiposity associations were not modified by sex; p-int > 0.4 for all biomarkers.
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Incident stroke, Ischemic stroke, IHD and AMI	(0) Non-significant HRs in main model 3 for all outcomes, with overlapping 95% CIs between sexes.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Pyko et al. (2019)	Stockholm County, Sweden	Longitudinal CEANS cohort including 20,012 individuals from 4 subcohorts, aged 35-104 years (mean 60) at entry	Road traffic, railway and aircraft noise (Lden) 1-5 years prior at most exposed façade accounting for residential history	IHD, MI, stroke and ischemic stroke (IS) incidence	For men vs. women. (+) **IHD: road traffic** 0.86 (0.79, 0.94) vs. 1.11 (1.00, 1.22); **railway** 1.00 (0.90, 1.11) vs. 1.02 (0.91, 1.14); **aircraft** 0.90 (0.78, 1.03) vs. 1.25 (1.09, 1.44). (+) **MI: road traffic** 0.84 (0.74, 0.94) vs. 1.17 (1.03, 1.34); **railway** 1.03 (0.89, 1.19) vs. 1.06 (0.91, 1.24); **aircraft** 0.94 (0.78, 1.13) vs. 1.29 (1.06, 1.56). (0) **Stroke: road traffic** 0.99 (0.89, 1.11) vs. 1.02 (0.91, 1.14); **railway** 0.97 (0.84, 1.11) vs. 1.13 (1.00, 1.27), **aircraft** 0.86 (0.72, 1.03) vs. 1.06 (0.89, 1.25). (0) **IS: road traffic** 0.96 (0.85, 1.09) vs. 1.01 (0.89, 1.14); **railway** 1.01 (0.86, 1.17) vs. 1.15 (1.01, 1.31), **aircraft** 0.79 (0.64, 0.98) vs. 1.07 (0.89, 1.29). Per 10 dB Lden.
Sørensen et al. (2012)	Copenhagen and Aarhus, Denmark	Cohort of Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2006 (mean 9.8 years)	Road traffic noise (Lden)	MI incidence	(0) **IRR men**: 1.14 (1.03, 1.26), **IRR women:** 1.06 (0.91, 1.23); p-int = 0.37. Per 10 dB.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Selander et al. (2009)	Stockholm County, Sweden	Case-control study conducted 1992-1994, in the Stockholm Heart Epidemiology Program, including 3666 participants (1571 cases; 2095 controls). Included adults between 45–70 years old with no history of MI	Road traffic noise (LAeq,24 above 50 dBA vs. below) accounting for address history.	Incident fatal and non-fatal myocardial infarction (MI)	(0) No difference between men and women, both will null associations (exact ORs not provided).
Mental health					
Orban et al. (2016)	Three large adjacent cities (Bochum, Essen, and Mülheim/Ruhr) in western Germany	Heinz Nixdorf Recall study (HNR), including 3300 adults 45 to 75 years at baseline (2000-2003). Analysed baseline and 5-year follow-up.	Road traffic noise (Lden and Lnight) from strategic mapping	Depressive symptoms during previous week, assessed with 15-item Center for Epidemiologic Studies Depression (CES-D) scale, and antidepressant medication intake	(0) Null associations between Lden >55 vs. <= 55 dB for both men and women.
Halonen et al. (2014)	Finland	Cross-sectional analysis in cohort of public sector employees, including >4000 men and women (mean age 50, range 21-76 years)	Road traffic noise (Lden) from 10m maps	Self-rated health and register-based use of antidepressants, anxiolytics, and hypnotics. Potentially vulnerable individuals (that may be noise sensitive) were identified using high trait anxiety scores	(0) **Medication use**: null associations for both sexes.
Self-reported health status					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Dzhambov et al. (2023)	Sofia, Bulgaria	Cross-sectional population-based survey of 917 adults responding to questionnaire on poor self-rated health.	Road traffic, railway and aircraft nosie (Lden) from 10m strategic noise maps	Poor self-rated health (PSRH). Obtained from a single question "In general, how would you rate your health?", with no specific time frame reference. Responses were on a 5-pt scale.	(0) No evidence of effect modification by sex.
Kodji et al. (2023)	Around 3 airports (Paris-Charles de Gaulle, Lyon Saint-Exupéry and Toulouse-Blagnac), France	DEBATS, longitudianl analysis of 1244 participants over 18 years living around 3 French airports.	Aircraft noise (Lden and LAeq24h), maps	Self-reported health status (SRHS)	(~) **OR men**: 1.58 (1.05, 2.37), **OR women:** 0.99 (0.70, 1.40). Per 10 dB Lden and after controlling for noise annoyance.
Baudin et al. (2021)	Areas around 3 major airports in France	Cross-sectional, 1242 participants over 18 years, living near airports (DEBATS study)	Aircraft noise (Lden)	Self-rated health status (SRHS). From interview question: "In general, would you say that your health is excellent, good, fair, or poor?".	(+) **OR men:** 1.55 (1.01, 2.39), **OR women:** 1.01 (0.69, 1.45). **OR for men highly sensitive to noise**: 3.26 (1.19, 8.88), p-int = 0.05. Per 10 dB Lden.
Mutz et al. (2021)	United Kingdom	UK Biobank, including 307,378 adults. Cross-sectional analysis	Road traffic noise (Lden)	Health status (from algorithm), preexisting disease, self-reported health	(0) No difference in the null association by men vs. women for any of the outcomes.
Halonen et al. (2014)	Finland	Cross-sectional analysis in cohort of public sector employees, including >4000 men and women (mean age 50, range 21-76 years)	Road traffic noise (Lden) from 10m maps	Self-rated health and register-based use of antidepressants, anxiolytics, and hypnotics. Potentially vulnerable individuals (that may be noise sensitive) were identified using high trait anxiety scores.	(+) Poor self-rated health: for exposure >60 dB vs. <=45 dB, **OR for men**: 1.58 (1.14, 2.21), **OR for women**: 0.91 (0.77, 1.08).

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Sleep disturbance					
Gong et al. (2024)	Living in Local Authority Districts whole or partly covered by noise contours of four major airports (London Heathrow, London Gatwick, Birmingham and Manchester), United Kingdom	UK Biobank cohort study, participants 40-69 years at recruitment (2006-2010). Cross-sectional (n>18000) and repeated cross-sectional design (n>84000), depending on outcome	Aircraft noise contours (Lnight) assigned to postcode and categorised in 5 dB steps	Objective and subjective sleep disturbance, defined separately by actimetric data (cross-sectional) and self-report (repeated cross-sectional)	(0) Generally little difference in associations by sex
Röösli et al. (2014)	Basel, Switzerland	Questionnaire with follow-up 1 year later, 1375 participants in main study, 120 participants in nested diary study with actigraphy	Road traffic noise (Lnight) at residential address from noise cadaster, in categories	Self-reported sleep disturbance, self-reported daytime sleepiness score, acute self-reported sleep quality, measured sleep efficiency and measured total sleep duration	(+) Significantly **poorer self-reported sleep quality in men** (-0.81 [-1.40, -0.23]) vs. **women** (-0.30 [-0.77, 0.17]) comparing Lnight >55 dB vs. reference; p-int = 0.041). (+) Significantly **shorter sleep duration in men** (-1.54 [-2.32, -0.76]) vs. **women** (0.58 [-0.10, 1.25]) comparing Lnight >55 dB vs. reference; p-int < 0.001).
Cognition					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Wu et al. (2024)	Sweden	Swedish National study on Aging and Care in Kungsholmen (SNAC-K), including 2594 dementia-free participants aged 60+ years followed up to 16 years	Road traffic, railway and aircraft noise (Lden) most exposed façade, accounting for address history	GCS (global cognition score) and CIND (cognitive impairment, no dementia)	(0) No difference in GCS nor CIND for any noise source, in models stratified by sex; p-int > 0.11.
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) No difference in global cognitive score by sex, overlapping 95% CIs (exact estimates not given).
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) No difference in MCI by sex, overlapping 95% CIs (exact estimates not given).
Mortality					
Zhang et al. (2024)	United Kingdom	UK Biobank, including 41,222 participants with chronic respiratory disease at baseline. Longitudinal analysis was mean follow-up of 12 years	Road traffic noise (Lden)	All-cause, respiratory disease (RD) and non-respiratory disease (non-RD) mortality	(~) **RD mortality:** (1.24 (1.02, 1,50); higher in men than women (p-int = 0.51).

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Sørensen et al. (2023)	Denmark	Nation-wide cohort including 2.6 million Danes aged 50 years and older, followed on average for 11.7 years (600,492 natural deaths)	Road traffic and railway noise (Lden) at most (LdenMax) and least (LdenMin) exposed facades considering residential history	Natural cause, cardiovascular, respiratory and cancer mortality	(0) No difference in relation to **road traffic noise LdenMax**; e.g. **natural mortality HR men**: 1.09 (1.09, 1.10), **HR women:** 1.09 (1.09, 1.10). (~) HRs generally slightly higher in men than women for **road traffic noise LdenMin**; e.g. **natural mortality HR men**: 1.12 (1.11, 1.13), **HR women:** 1.08 (1.07, 1.09). Per 10 dB.
Vienneau et al. (2023)	Switzerland	Cohort, SNC with 4.2 mil adults over 30 years followed for up to 15 years.	Total transportation noise (road traffic, railway, aircraft) (Lden)	Natural cause mortality	(+) Higher **HRs for men**: 1.059 (1.053, 1.064), **HR women:** 1.029 (1.024, 1.035) after considering $PM_{2.5}$. Per 10 dB Lden.
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342, 566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	CVD and all-cause mortality	(+) Associations only found in men. **HR all-cause mortality**: 1.09 (1.05, 1.14), **HR CVD mortality**: 1.08 (0.99, 1.19). Associations attenuated after adjusting for $PM_{2.5}$. Per 10 dB Lden.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Vienneau et al. (2022)	Switzerland	Cohort, SNC with 4.1 mil adults over 30 years followed for up to 15 years.	Road traffic, railway and aircraft noise (Lden)	Cause specific CVD mortality	(+) CVD mortality and road traffic noise, HR men: 1.049 (1.042, 1.057), HR women: 1.011 (1.004, 1.018); p-int < 0.0001. Same pattern found for blood pressure-related, IHD, heart failure, and stroke mortality with road traffic noise, and all CVD with railway noise. (0) No differences in relation to aircraft noise. Per 10 dB Lden.
Thacher et al. (2020)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of 52,758 Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2016 (median 19.5 years)	Road traffic noise (Lden) at most and least exposed facades and including residential history.	All-cause and CVD mortality	(0) Similar HR by sex at most and least exposed facades: **all-cause mortality HR men**: 1.09 (1.05, 1.13), **HR women:** 1.07 (1.02, 1.11) per IQR LdenMax; p-int = 0.53. (0) CVD mortality **HR men:** 1.12 (1.05, 1.20), **HR women**: 1.13 (1.02, 1.25) per IQR LdenMax; p-int = 0.93.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
(Pyko et al., 2019)	Stockholm County, Sweden	Longitudinal CEANS cohort including 20,012 individuals from 4 subcohorts, aged 35-104 years (mean 60) at entry	Road traffic, railway and aircraft noise (Lden) 1-5 years prior at most exposed façade accounting for residential history	IHD and stroke mortality	(0) For men vs. women. **IHD: road traffic** 0.98 (0.81, 1.18) vs. 1.19 (0.97, 1.47); **railway** 1.04 (0.83, 1.30) vs. 1.09 (0.87, 1.37), **aircraft** 1.06 (0.80, 1.41) vs. 1.32 (0.99, 1.76). **Stroke: road traffic** 0.88 (0.64, 1.21) vs. 1.07 (0.79, 1.45); **railway** 1.11 (0.77, 1.60) vs. 1.18 (0.86, 1.63); **aircraft** 1.39 (0.87, 2.21) vs. 1.26 (0.82, 1.94). Per 10 dB Lden.

In Key findings:
‘p-int’ refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups

3.3.1 Cardiometabolic disease

The study using the Stockholm County CEANS cohort by Pyko et al. (2019), described in section 3.2.1, investigating source specific transportation noise in relation to IHD, MI, stroke and ischemic stroke incidence explored potential effect modification by sex. While no overall associations between the noise exposures and CVD incidence were found, higher risk was found in women compared to men for some combinations. Specifically, the risk was statistically higher for IHD incidence in women compared to men for road traffic noise (1.11 [1.00, 1.22] vs. 0.86 [0.79, 0.94] per 10 dB Lden) and for aircraft noise (1.25 [1.09, 1.44] vs. 0.90 [0.78, 1.03] per 10 dB Lden). The association between MI incidence and road traffic noise was also significantly higher in women (1.17 [1.03, 1.34] vs. 0.84 [0.74, 0.94] per 10 dB Lden).

Otherwise, most studies exploring stratifying by sex have not found difference. The Stockholm County case-control study by Selander et al. (2009) on road traffic noise and incident myocardial infarction, described in section 3.2.1, found no difference in risk of MI between men and women, both showing null associations. The Diet, Cancer and Health cohort study by Sørensen et al. (2012), described in 3.2.1, included over 57000 adults between the ages of 50 and 64 years at enrolment. It reported higher risk of MI in relation to road traffic noise in men at 14% (1.14 [1.03, 1.26] vs. 6% in women (1.06 [0.91, 1.23]; p-int = 0.37), though with overlapping confidence intervals indicting any difference between the sexes was not significant. The study in Brno, Czech Republic described in 3.1.2 also investigated whether the cross-sectional association between noise and adiposity was modified by sex (Bartoskova Polcrova et al., 2025). The authors found that the associations were not modified by sex for any of the tested biomarkers (BMI, waist circumference, body fat percentage and visceral fat area; p-int > 0.4). The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342,566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline and followed for a median of 9 years. For the incident CVD outcomes, the main analysis showed only showed a borderline significant association for road traffic noise and incident stroke that attenuated after adjusting for $PM_{2.5}$. The study found no sign of effect modification by sex (HR men: 1.06 [0.99, 1.14] and HR women: 1.04 [0.95, 1.13] per 10 dB Lden) with the associations attenuating to null after adjusting for $PM_{2.5}$.

3.3.2 Mental health

Two studies on road traffic noise and mental health found no difference in associations between men and women. Orban et al. (2016) used strategic noise mapping to evaluate exposure in relation to depressive symptoms in the Heinz Nixdorf Recall (HNR) study. Participants were recruited between 2000-2003 from Bochum, Essen, and Mülheim/Ruhr, three large adjacent cities in western Germany, for a population of 3300 adults 45 to 75 years at baseline. The outcome was defined based on questionnaire and medication intake. Depressive symptoms the during previous week were queried using the 15-item Center for Epidemiologic Studies Depression (CES-D) scale while antidepressant medication intake was determined by asking participants to bring medication to the interview. Stratified results by sex and by SES (using education as the indicator) were considered to explore potential effect modification. Regarding sex, null associations between Lden >55 vs. <= 55 dB and depressive symptoms were observed for both men and women. A cross-sectional analysis within the Finnish Public Sector Study, by Halonen et al. (2014) and described in 3.1.2, explored associations between road traffic noise and self-rated health and register-based use psychotropic medications. For both sexes, the associations between road traffic noise and psychotropic medication (antidepressants, anxiolytics, and hypnotics) were null.

3.3.3 Self-reported health status

Several studies looked into the differences in the relationship between transportation noise and self-reported health status (SRHS) by sex, with mixed results. The cross-sectional population-based survey in Sofia, Bulgaria mentioned in 3.2 found no difference between men and women in self-rated poor

health in relation to transportation noise (Dzhambov et al., 2023). The UK Biobank study by Mutz et al. (2021), described in 3.2.2 that included 307,378 adults also found no overall association between road traffic noise (Lden) and SRHS. Further, they reported no difference between men and women for any of the studied outcomes. The cross-sectional analysis within the Finnish Public Sector Study, by Halonen et al. (2014) and described in 3.1.2, however, reported the OR for poor self-rated health in men was elevated at 1.58 (1.14, 2.21) while in women there was a null association (0.91 [0.77, 1.08]). This was for road traffic noise exposure >60 dB vs. <=45 dB. As the 95% confidence intervals do not overlap, this indicates that men are more susceptible than women.

Two studies specifically studied aircraft noise, both finding no difference in effects by sex. A cross-sectional study including of more than 1200 participants over 18 living near 3 major airports in France (DEBATS study), enquired about SRHS of men vs. women with a question: "In general, would you say that your health is excellent, good, fair, or poor?" The study found an association between aircraft noise and fair/poor self-reported health status only in men (OR=1.55 [95%CI 1.01, 2.39] vs. 1.01 [0.69, 1.45] for women, per 10 dB Lden). Notably, the association was stronger in men who were highly sensitive to noise (OR=3.26 [1.19, 8.88], per 10 dB Lden) and in a subset who had lived at the same address at least 5 years (Baudin et al., 2021).

The DEBATS study by Kodji et al. (2023) also evaluated the mediation effect of noise annoyance and sensitivity on the relationship between aircraft noise exposure (Lden) and SRHS. The population included 1244 participants over 18 years of age, living around 3 major airports in France. The outcome was assessed by the question "In general, would you say that your health is excellent, fair or poor?". After considering annoyance to aircraft noise, men experienced worse SRHS in relation to aircraft noise than women with odds ratios of 1.58 (1.05, 2.37) vs. 0.99 (0.70, 1.40) per 10 dB Lden. Similar results were found for LAeq24h. The associations also persisted in a subset of those with stable residential address before and during follow-up.

3.3.4 Sleep disturbance

The UK Biobank study on aircraft noise and sleep disturbance, mentioned in 3.1.3, also looked at difference in objective and subjective measures of sleep by sex. In general, they found little difference in both sets of analyses suggesting aircraft noise on sleep disturbance is not modified by sex (Gong et al., 2024).

A study in Basel, Switzerland by (Röösli et al., 2014) found differences in sleep outcomes related to road traffic noise by sex. The study was specifically designed to evaluate gender differences in sleep disturbance due to road traffic noise. Conducted in 2008 with a follow-up 1 year later, the study used questionnaire to collect subjective data on sleep from 1375 participants. It also included a nested diary study with 120 participants for which sleep was objectively assessed with actigraphy. Outcomes included self-reported sleep disturbance, self-reported daytime sleepiness score, acute self-reported sleep quality, measured sleep efficiency and measured total sleep duration. Exposure was based on the Basel noise cadaster to assign nighttime road traffic noise at the residence in categories (<30, 30-40, 40-55 and >55 dB Lnight). All analyses were stratified by sex. Differences in response by sex were found in the highest exposure category of >55 dB Lnight for two of the six outcomes, with men being the more vulnerable. In particular, the study found that men had significantly poorer self-reported sleep quality than women (-0.81 [-1.40, -0.23] vs. -0.30 [-0.77, 0.17] comparing Lnight >55 dB vs. reference, p-int = 0.041). Men also had significantly shorter sleep duration than women (-1.54 [-2.32, -0.76] vs. 0.58 [-0.10, 1.25] comparing Lnight >55 dB vs. reference, p-int < 0.001).

3.3.5 Cognition

Two different study populations were used to explore cognition in relation to road traffic noise, and to investigate potential effect modification by sex. First, the Swedish National study on Aging and Care in

Kungsholmen (SNAC-K) was used by Wu et al. (2024) to study source-specific transportation noise in relation to cognitive function in older adults (described in section 3.1.4). In addition to effect modification by age, the authors explored global cognition score and cognitive impairment, no dementia (CIND) by sex. None of the transportation noise sources were associated with decline in global cognition score for either sex, with p-int = 0.994, 0.932, and 0. 211 respectively for road traffic, aircraft and railway noise. CIND incidence was also not significantly different between the sexes, with p=interactions of 0 171, 0.363 and 0.110 respectively for road traffic, aircraft and railway noise.

The population-based study Heinz Nixdorf Recall study (2006–2008) in the Ruhr area of Germany, described in 3.1.2, cross-sectionally evaluated cognitive performance in relation to road traffic noise in 4086 participants with a suite of six tests (Tzivian et al., 2016a). While an association in the full population was only found between road traffic noise Lden above the 60 dB threshold and global cognitive score, global cognitive score did not differ by sex as indicated by overlapping 95% confidence intervals in the sex-stratified models (exact estimates not given). Tzivian et al. (2016b) also studied mild cognitive impairment in the same cohort. For this outcome, a significant association was found for both Lden and Lnight above the thresholds in the full study population. There was no difference in mild cognitive impairment, however, by sex, as shown by the overlapping 95% confidence intervals in the sex-stratified models (exact estimates not given).

3.3.6 Mortality

A number of studies have been on all-cause, natural-cause, or cause-specific mortality and transportation noise, some finding differences by sex and others not. As described in 3.2.7, Sørensen et al. (2023) studied natural and cause-specific mortality associations with road traffic and railway noise in the nation-wide Danish cohort. It included 2.6 million adults over 50 years of age for an average of 11.7 years. While they found increased risk of mortality in relation to road traffic noise at the maximum exposed façade for all outcomes (natural cause, CVD, respiratory and cancer), they found no indication of effect modification by sex. Similar associations with road traffic noise were found for both sexes for all outcomes (e.g. natural cause mortality, HR were 1.09 (1.09, 1.10) for men and 1.09 (1.09, 1.10) for women, per 10 dB LdenMax road traffic noise). For the minimum exposed façade, however, HRs tended to be slightly higher in men than women for natural cause, CVD and cancer mortality (e.g. natural mortality: 1.12 (1.11, 1.13) in men, 1.08 (1.07, 1.09) in women per 10 dB LdenMin). Effect modification was not explored for railway noise, however this source was included as an adjustment in the analyses on road traffic noise.

Thacher et al. (2020) used the Diet, Cancer and Health cohort including 52,758 Danish born persons aged 50-64 years, with no history of cancer, to investigate mortality in relation to road traffic noise at the most and least exposed facades. A number of cause-specific mortality outcomes were included, with main effects found for all-cause mortality and CVD mortality. These two outcomes were subsequently included in analyses into the potential effect modification by sex and by socioeconomic status. The study found similar HR when using either the most or least exposed facades, with slightly stronger effects in relation to the most exposed facade. For all-cause mortality, the HRs were 1.09 (1.05, 1.13) for men and 1.07 (1.02, 1.11) for women, per IQR LdenMax (p-int = 0.53). For CVD mortality, the sex specific HRs were 1.12 (1.05, 1.20) for men and 1.13 (1.02, 1.25) for women, per IQR LdenMax (p-int = 0.93). Across outcomes there was no evidence of effect modification by age.

The Stockholm County CEANS cohort by Pyko et al. (2019), described in section 3.2.1, investigated IHD and stroke mortality in relation to source specific transportation noise, including analyses on effect modification by sex. The study found no overall associations, and although differences between groups were not statistically significant, for IHD mortality higher HRs were found for women compared to men in relation to both road traffic noise (1.19 [0.97, 1.47] vs. 0.98 [0.81, 1.18] per 10 dB Lden) and aircraft noise (1.32 [0.99, 1.76] vs. 1.06 [0.80, 1.41] per 10 dB).

The remaining studies did find evidence of effect modification. First, the UK Biobank study by Hao et al. (2022), described in 3.1.1, which included 342,566 participants 40-69 years at recruitment (2006-2010) free of CVD at baseline. It found that all-cause and CVD mortality were only associated with road traffic noise exposure in men with HRs of 1.09 (1.05, 1.14) and 1.08 (0.99, 1.19) per 10 dB Lden, respectively. On adjusting for $PM_{2.5}$, however, all-cause mortality attenuated to 1.03 (0.99, 1.08) per 10 dB and CVD mortality attenuated to the null.

Zhang et al. (2024) also used the UK Biobank to investigate the association of road traffic noise with mortality with a special focus on individuals with chronic respiratory diseases. The study included >41,000 participants with COPD, asthma, interstitial lung disease, bronchiectasis and chronic bronchitis at baseline between 2006 and 2010. Participants were followed in a longitudinal analysis for up to 12 years, with outcomes of interest including all-cause mortality, respiratory disease mortality and non-respiratory mortality. In the full study population, the highest risk was for respiratory disease mortality with a HR of 1.24 (1.02, 1,50) per 10 dB Lden. Their analyse on effect modification indicated that the association for respiratory disease mortality was strongest in men (2.26 [1.32, 3.86)] compared to women (1.14 (0.60, 2.15)] in the highest exposed category vs. reference, though the difference was not significant (p-int = 0.51).

As described in 3.2.7, Vienneau et al. (2022) used the Swiss National Cohort, with 4.1 million adults over 30 and a mean follow-up of 13.4 years, to study cause-specific CVD mortality in relation to road traffic, railway and aircraft noise. Effect modification by sex was also explored, with results for all CVD mortality presented both as relative and absolute risk. The HR for men were significantly higher compared to women for the associations between road traffic noise and all CVD, blood pressure-related, IHD, heart failure, and stroke mortality. For CVD mortality, the estimates were: 1.049 (1.042, 1.057) for men, 1.011 (1.004, 1.018) for women per 10 dB road traffic noise (p-int < 0.0001). This same pattern was found for all CVD only in relation to railway noise, and no difference between sex was found in relation to aircraft noise. Converting the relative risk to absolute risk also showed that men have a higher absolute risk for CVD mortality compared to women (chapter 2.4). Vienneau et al. (2023) used the same Swiss National Cohort to study mortality in relation to total transportation noise (energetic sum of road traffic, railway and aircraft noise), in the context of co-exposure with air pollutants. Stratified analysis by sex showed that total transportation noise was associated with significantly higher HRs for natural cause mortality for men compared to women (1.059 [1.053, 1.064] vs. 1.029 [1.024, 1.035] per 10 dB Lden after considering $PM_{2.5}$).

3.4 Socioeconomic status and work

The main body of evidence presented here is on studies that have stratified the association between noise exposure and various health outcomes by aspects of socioeconomic status including SES score, education level, job level and income. In addition, particular occupational situations like working night shifts are mentioned (Table 3.4). In this context, SES may be an indicator for other factors determining vulnerability to noise such as restricted access to health system, restricted financial means for therapies, reduced health literacy or stressful life situations amplifying effects of environmental exposures.

Table 3.4 Summary table of studies on socioeconomic status and work

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Cardiometabolic disease					
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Stroke incidence	(0) No difference. **HR ≥13 yrs education**: 1.10 (1.01, 1.20), **HR <13 yrs:** 1.05 (0.98, 1.13); p-int = 0.387. Per 10 dB Lden.
Pyko et al. (2019)	Stockholm County, Sweden	Longitudinal CEANS cohort including 20,012 individuals from 4 subcohorts, aged 35-104 years (mean 60) at entry	Road traffic, railway and aircraft noise (Lden), 1-5 years prior at most exposed façade accounting for residential history	IHD incidence	(0) No difference in HR for education levels low, medium and high; p-int = 0.89 (exact HR not provided).
Sørensen et al. (2012)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2006 (mean 9.8 years)	Road traffic noise (Lden)	MI incidence	(0) No difference. **IRR by years of education** (<=7, 8-10 and >10): 1.07 (0.95, 1.20), 1.14 (1.01, 1.30) and 1.22 (1.00, 1.47) respectively; p-int = 0.41. Per 10 dB Lden.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Selander et al. (2009)	Stockholm County, Sweden	Case-control study conducted 1992-1994, in the Stockholm Heart Epidemiology Program, including 3666 participants (1571 cases; 2095 controls). Included adults between 45–70 years old with no history of MI	Road traffic noise (LAeq,24 above 50 dBA vs. below) accounting for address history	Incident fatal and non-fatal myocardial infarction (MI)	(0) No difference by job category (blue collar, low-level white collar and high-level white collar), all with null associations (exact ORs not provided).
Mental health					
Orban et al. (2016)	Three large adjacent cities (Bochum, Essen, and Mülheim/Ruhr) in western Germany	Heinz Nixdorf Recall study (HNR), including 3300 adults 45 to 75 years at baseline (2000-2003). Analysed baseline and 5-year follow-up	Road traffic noise (Lden and Lnight) from strategic mapping	Depressive symptoms during previous week, assessed with 15-item Center for Epidemiologic Studies Depression (CES-D) scale, and antidepressant medication intake	(~) Indication of elevated **RR Education <=13 years**: 1.43 (1.10, 1.85), **RR Education >13 years:** 0.92 (0.56, 1.53) for exposure to Lden >55 vs. <= 55 dB.
Self-reported health status					
Dzhambov et al. (2023)	Sofia, Bulgaria	Cross-sectional population-based survey of 917 adults responding to questionnaire on poor self-rated health.	Road traffic, railway and aircraft noise (Lden) from 10m strategic noise maps	Poor self-rated health (PSRH). Obtained from a single question "In general, how would you rate your health?", with no specific time frame reference. Responses were on a 5-pt scale	(+) **Aircraft noise**, increased OR for **PSHR in low** (2.46 [1.29, 4.69]) vs. **higher educated** or **living in low** (1.43 [1.26, 1.62]) vs. **higher income areas**; p-int < 0.013. **Railway noise**, increased OR for **PSHR in low** (1.23 [1.11, 1.36]) vs. **higher income areas**; p-int = 0.006. (0) **Road traffic noise**, no association.
Sleep disturbance					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Gong et al. (2024)	Living in Local Authority Districts whole or partly covered by noise contours of four major airports (London Heathrow, London Gatwick, Birmingham and Manchester), United Kingdom	UK Biobank cohort study, participants 40-69 years at recruitment (2006-2010). Cross-sectional (n>18000) and repeated cross-sectional design (n>84000), depending on outcome	Aircraft noise contours (Lnight) assigned to postcode and categorised in 5 dB steps	Objective and subjective sleep disturbance, defined separately by actimetric data (cross-sectional) and self-report (repeated cross-sectional)	(~) Generally little difference between in associations for low SES vs. total sample except for the over 55 year-olds showing higher sleep duration, higher relative amplitude, and lower intra-daily variability.
Infertility					
Sørensen et al. (2024)	Denmark	Nationwide prospective cohort of 0.9 mil women and men (aged 30-34) followed from 2000 to 2017	Road traffic noise (Lden) at maximum exposed façade	Incident infertility	(0) No difference in risk of infertility in men (37-45 yr) or women (35-45 yr), **by education nor by income quartile**. E.g, women-education: HR for mandatory 1.15 (1.03, 1.26), secondary 1.16 (1.11, 1.22), and further 1.11 (1.05, 1.16). Per IQR Lden.
Cognition					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) No difference in global cognitive score by **SES (low-medium vs. high)**, overlapping 95% CIs (exact estimates not given).
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) No difference in MCI by **SES (low-medium vs. high)**, overlapping 95% CIs (exact estimates not given).
Cancer					
Sørensen et al. (2021)	Denmark	Administrative cohort of 1.8 million cancer-free women at baseline, followed for up to 16 years	Road traffic noise (Lden) at most and least exposed façade accounting for address history	Breast cancer	(0) No effect modification using the LdenMax; p-trend = 0.72. (+) Higher effects in the **low and medium educated** groups compared to the **highly** educated using LdenMin; p-trend 0.07.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Andersen et al. (2018)	Denmark	Danish Nurse Cohort, on 22,466 female nurses aged 44+ years at 1993/1999 recruitment. Longitudinal analysis with mean follow-up of 15.7 years	Road traffic noise (Lden) at most exposed façade	Breast cancer incidence	(~) **HR night shifts:** 1.86 (0.97, 3.57), **HR no night shifts:** 1.16 (1.00, 1.35); p-int = 0.38. (+) **HR night shift and ER+:** 3.36 (1.48, 7.63), **HR no night shift and ER+:** 1.21 (1.02, 1.43); p-int = 0.05. (0) **HR BMI ≤30 kg/m²:** 1.86 1.18 (1.03, 1.35), **HR BMI >30 kg/m2:** 1.03 (0.65, 1.65); p-int = 0.75. Per 10 dB Lden.
Mortality					
Sørensen et al. (2023)	Denmark	Nation-wide cohort including 2.6 million Danes aged 50 years and older, followed on average for 11.7 years (600,492 natural deaths)	Road traffic and railway noise (Lden) at most (LdenMax) and least (LdenMin) exposed facades considering residential history	Natural cause, cardiovascular, respiratory and cancer mortality	(0) **Education level**: no difference in relation to **road traffic noise LdenMax**; e.g. **natural mortality HRs:** 1.09 (1.09, 1.10) for **mandatory**, 1.09 (1.08, 1.10) for **secondary** and 1.10 (1.09, 1.11) for **further** education. Per 10 dB.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342, 566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	CVD and all-cause mortality	(~) Indication of elevated **CVD mortality, HR ≥13 yrs education:** 1.20 (1.07, 1.35), **HR <13 yrs:** 1.07 (0.96, 1.19); p-int = 0.159. (0) **All-cause mortality, HR ≥13 yrs education:** 1.09 (1.04, 1.15), **HR <13 yrs:** 1.07 (1.02, 1.12); p-int = 0.501. Per 10 dB Lden.
Thacher et al. (2020)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of 52,758 Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2016 (median 19.5 years)	Road traffic noise (Lden) at most and least exposed facades, and including residential history	All-cause and CVD mortality	(~) Suggested increased risk in **all-cause mortality and LdenMin** with increasing education level; p-int = 0.10. Otherwise no clear trend or difference in HRs. p-int were 0.38, 0.63 and 0.30 for **LdenMax and all-cause mortality, LdenMax and CVD mortality and LdenMin and CVD mortality**, respectively.

In Key findings:
‘p-int’ refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups

3.4.1 Cardiometabolic disease

Several studies have explored whether the association between noise exposure and CVD incidence is influenced by socioeconomic status, all of which did not find clear evidence of differences between groups. The study using the Stockholm County CEANS cohort by Pyko et al. (2019), described in section 3.2.1, looked into potential differences in the associations between source specific transportation noise and IHD incidence SES. They found no difference in the effects by education defined as levels low, medium and high (p-int = 0.89, exact HR not provided). The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342, 566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline to study stroke incidence. It also found no sign of effect modification by socioeconomic status, defined as education (HR for ≥13 years of education 1.10 (1.01, 1.20) per 10 dB Lden vs. HR for <13 years of 1.05 (0.98, 1.13), p-int = 0.387).

Likewise, the older studies did not see differences. The Stockholm County case-control study by Selander et al. (2009) on road traffic noise and incident myocardial infarction, described in section 3.2.1, used job category (defined as blue collar, low-level white collar and high-level white collar) as the indicator of socioeconomic status. The study found no difference in relationship between road traffic noise and incident MI by job category, with null associations shown in all groups (exact ORs not provided). Finally, the Diet, Cancer and Health cohort study, described in 3.2.1, on road traffic noise exposure and MI incidence looked at differences in risk by education as a proxy for socioeconomic status. Education was defined in three groups, based on <=7 years, 8-10 years and >10 years with IRRs of 1.07 (0.95, 1.20), 1.14 (1.01, 1.30) and 1.22 (1.00, 1.47) per 10 dB respectively. The overlapping 95% confidence intervals and p-int = 0.41 indicate no difference in risk between the groups (Sørensen et al., 2012).

3.4.2 Mental health

As described in 3.3.2, road traffic noise in relation to depressive symptoms was studied in the German Heinz Nixdorf Recall (HNR) study (Orban et al., 2016). The authors included models stratified by SES to explore potential effect modification, using education as the SES indicator. They found higher RR with lower vs. higher education, in relation to road traffic noise Lden >55 vs. <= 55 dB, though the difference between groups was not significant (education <=13 years RR: 14.3 (1.10, 1.85) vs. education >13 years RR: 0.92 (0.56, 1.53).

3.4.3 Self-reported health status

The cross-sectional population-based survey in Sofia, Bulgaria mentioned in 3.2.2 asked over 900 adults asked to self-rate their general health and explored the responses in relation to transportation noise exposures and accounting for co-exposures including greenspace and air pollution (Dzhambov et al., 2023). Regarding SES, they found that aircraft noise exposure was associated with increased odds of poor self-rated health (PSRH) amongst those with low (2.46 [1.29, 4.69]) vs. higher education or living in low (1.43 [1.26, 1.62]) vs. higher income areas (p-int < 0.013). Railway noise exposure was also associated with increased odds of PSRH in those living in low (1.23 [1.11, 1.36]) vs. higher income areas (p-int = 0.006). No association between road traffic noise and PSRH was found. The authors speculate this is due to the low exposure contrast or exposure misclassification as exposure assessment was based on noise mapping.

3.4.4 Sleep disturbance

The UK Biobank study on aircraft noise and sleep disturbance, mentioned in 3.1.3, also looked at difference in objective and subjective measures of sleep by socioeconomic status using household income as the indicator. Overall, they found little difference between in associations for low SES vs.

the total sample except for the over 55 year-olds where they found higher sleep duration, higher relative amplitude, and lower intra-daily variability (Gong et al., 2024).

3.4.5 Infertility

The nationwide cohort from Denmark by (Sørensen et al., 2024) on the relationship between road traffic noise and incident infertility in both men and women of reproductive age, described in section 3.2.4, also explored effect modification by socioeconomic status in the older adults. Specifically, education was defined in three groups as mandatory, secondary or vocational and medium or long. The respective HRs for men aged 37-45 years were 1.09 (0.99, 1.21), 1.10 (1.05, 1.16) and 0.95 (0.88, 1.03) per IQR road traffic noise Lden at the maximum exposed façade. For women aged 35-45 years, the respective HRs were 1.15 (1.03, 1.26), 1.16 (1.11, 1.22), and 1.11 (1.05, 1.16) per IQR Lden. Personal income was defined in quartiles. These associations for men were 1.00 (0.90, 1.12), 1.06 (0.99, 1.15), 1.11 (1.04, 1.20) and 1.03 (0.96, 1.11) per IQR Lden, and for women were 1.07 (0.98, 1.17), 1.14 (1.07, 1.21), 1.12 (1.06, 1.19) and 1.19 (1.12, 1.26) per IQR Lden. Overall, they found no difference in risk of infertility in men or women by education nor by income quartile.

3.4.6 Cognition

The population-based study Heinz Nixdorf Recall study (2006–2008) in the Ruhr area of Germany, described in 3.1.2, cross-sectionally evaluated cognitive performance in relation to traffic noise in 4086 participants with a suite of six tests (Tzivian et al., 2016a). In the full study population, an association was only found between road traffic noise Lden above the 60 dB threshold and global cognitive score. Thus, the authors investigated potential effect modification by socioeconomic status, stratifying on low-medium vs. high, finding no indications for effect modification by SES as per the overlapping 95% confidence intervals (exact estimates not given). Within the same Heinz Nixdorf Recall study (2006–2008) Tzivian et al. (2016b) conducted a cross-sectional study on road traffic noise and mild cognitive impairment. In the full study population, a significant association was found for both Lden and Lnight above the thresholds. When stratifying by low-medium vs. high SES, however, there was no difference in mild cognitive impairment by SES (exact estimates not given).

3.4.7 Cancer

Two studies have looked at the influence of situational factors on the relationship between road traffic noise and breast cancer. The administrative cohort in Denmark, described in section 3.2.6 was constructed to study transportation noise in relation to breast cancer incidence (Sørensen et al., 2021). It included analyses stratified by education defined in three groups: low, medium and high. There was no clear trend in the IRRs when using the maximum exposed façade (p-trend = 0.72); however, for the minimum exposed façade effects were higher in the low and medium educated groups compared to the highly educated (p-trend = 0.07).

Incidence of breast cancer in female nurses in relation to road traffic noise was also studied by Andersen et al. (2018) using the nationwide Danish Nurse Cohort. Here the focus was to examine the influence of shift work on the association. This longitudinal analysis included over 22,000 female nurses aged 44 years and older, followed for a mean of 15.7 years. The authors found indications of increased risk in women working night shifts (1.86 [0.97, 3.57] vs. not 1.16 [1.00, 1.35] per 10 dB Lden, p-int = 0.38). The association was only significantly different between groups, however, for those with ER+ breast cancer (3.36 [1.48, 7.63] night shift vs. 1.21 [1.02, 1.43] no night shift per 10 dB Lden, p-int = 0.05). The authors also explored the associations by BMI, finding no statistical difference between those with BMI ≤30 kg/m^2 compared to >30 kg/m^2 (e.g. for breast cancer with receptor status: 1.18 (1.03, 1.35) per 10 dB Lden for BMI ≤30 kg/m^2 vs. 1.03 (0.65, 1.65) for BMI >30 kg/m^2, p-int > 0.75).

3.4.8 Mortality

Three large cohorts have used education as an indicator of socioeconomic status, to see if it influences associations between transportation noise and mortality outcomes. The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342,566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline and followed for a median of 9 years. For the mortality outcomes, there was no sign of effect modification by socioeconomic status, defined as ≥13 years of education compared to <13 years. Specifically, for CVD mortality the respective HRs were 1.20 (1.07, 1.35) per 10 dB Lden and 1.07 (0.96, 1.19) (p-int = 0.159). For all-cause mortality, the respective HRs were 1.09 (1.04, 1.15) per 10 dB Lden and 1.07 (1.02, 1.12) (p-int = 0.501).

Natural and cause-specific mortality in relation to road traffic and railway noise was studied in the nation-wide Danish cohort by Sørensen et al. (2023), as described in section 3.2.7. The authors included analyses on road traffic noise at the maximum exposed façade stratified by education level. Three educations levels were defined: mandatory, secondary/vocational and medium/long education. Overall, and as indicated by overlapping 95% confidence intervals, they found no difference in mortality risk by education level for any of the mortality outcomes which included natural, cardiovascular, respiratory and cancer mortality. For natural mortality, for example, the HRs were 1.09 (1.09, 1.10), 1.09 (1.08, 1.10) and 1.10 (1.09, 1.11) per 10 dB LdenMax for mandatory, secondary/vocational, and medium/long education, respectively.

As described in section 3.3.6, Thacher et al. (2020) used the Diet, Cancer and Health cohort including 52,758 Danish born persons aged 50-64 years, with no history of cancer, to investigate mortality in relation to road traffic noise. Exposure was evaluated both at the most and least exposed facades. There was some suggestion for increasing risk with increasing education level for the association between noise at the least exposed façade and all-cause mortality. These HRs were 1.01 (0.97, 1.06), 1.05 (1.01, 1.09) and 1.10 (1.02, 1.17) respectively, with a p-int = 0.10. Otherwise, the analysis revealed no clear trend or difference in HRs by education. The interactions for the other combinations were not significant at p-int 0.38 for LdenMax and all-cause mortality, p-int = 0.63 for LdenMax and CVD mortality and p-int = 0.30 for LdenMin and CVD mortality.

3.5 Lifestyle and behavioural factors

This section focuses on studies looking at differences in noise effects by lifestyle and behavioural factors including diet, smoking, alcohol and physical activity (Table 3.5).

Table 3.5 Summary table of studies on work, lifestyle and behavioural factors

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Cardiometabolic disease					
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Stroke incidence	(0) No difference between groups: BMI (<30 kg/m^2 vs. ≥30 kg/m^2), current smoking (no vs. yes), physical activity (≥MET 600 min/w vs. <MET 600 min/w), fruit and vegetable consumption (high vs. low) with p-int > 0.592. (~) **HR sleep 7-8hr**: 1.03 (0.96, 1.11) vs. **HR sleep <7hr/≥8hr:** 1.13 (1.03, 1.24); p-int = 0.129). Per 10 dB Lden.
Pyko et al. (2019)	Stockholm County, Sweden	Longitudinal CEANS cohort including 20,012 individuals from 4 subcohorts, aged 35-104 years (mean 60) at entry	Road traffic, railway and aircraft noise (Lden) 1-5 years prior at most exposed façade accounting for residential history	IHD incidence	(0) No difference in HR for smoking (current, former, never), p-int = 0.88; physical activity (sedentary, moderate, regular), p-int = 0.34; alcohol consumption (daily, weekly, seldom, never) p-int = 0.28 (exact HR not provided).

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Sørensen et al. (2012)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2006 (mean 9.8 years)	Road traffic noise (Lden)	MI incidence	(~) IRR by **smoking status (never, former and current):** 1.24 (1.05, 1.47), 0.99 (0.85, 1.15), and 1.14 (1.02, 1.27) respectively; p-int = 0.11.
Selander et al. (2009)	Stockholm County, Sweden	Case-control study conducted 1992-1994, in the Stockholm Heart Epidemiology Program, including 3666 participants (1571 cases; 2095 controls). Included adults between 45–70 years old with no history of MI	Road traffic noise (LAeq,24 above 50 dBA vs. below) accounting for address history	Incident fatal and non-fatal myocardial infarction (MI)	(0) No difference between lifestyle defined by smoking (never, former, 1-10 g tobacco/day, 11-20g tobacco/day, >20 g tobacco/day), physical activity (yes, no), BMI (<27 kg/m2, >27 kg/m2) and job strain (no, yes). (~) However, indication of higher risk in former smokers. (exact ORs not provided).
Mental health					
Orban et al. (2016)	Three large adjacent cities (Bochum, Essen, and Mülheim/Ruhr) in western Germany	Heinz Nixdorf Recall study (HNR), including 3300 adults 45 to 75 years at baseline (2000-2003). Analysed baseline and 5-year follow-up.	Road traffic noise (Lden and Lnight) from strategic mapping	Depressive symptoms during previous week, assessed with 15-item Center for Epidemiologic Studies Depression (CES-D) scale, and antidepressant medication intake	(~) **RR for insomnia**: 1.62 (1.01, 2.59) vs. **RR for no insomnia**: 1.21 (0.94, 1.57) for exposure to Lden >55 vs. <= 55 dB.
Cognition					

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Wu et al. (2024)	Sweden	Swedish National study on Aging and Care in Kungsholmen (SNAC-K), including 2594 dementia-free participants aged 60+ years followed up to 16 years	Road traffic, railway and aircraft noise (Lden), most exposed façade, accounting for address history	GCS (global cognition score) and CIND (cognitive impairment, no dementia)	(0) Generally no difference in GCS nor CIND for any noise source, in models stratified by **physical activity (no to mild vs. high) or smoking status (ever vs. never vs. current);** p-int > 0.14. (~) Suggested elevated risk for **CIND in current smokers**, with HR of 1.96 (1.02, 3.76). Per 10 dB aircraft noise.
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) Regular physical activity (yes vs. no), BMI (≤30 vs. >30 kg/m^2), smoking (no vs. current/former) and alcohol drinks/week (≤6 vs. >6). No differences in global cognitive score between groups, overlapping 95% CIs (exact estimates not given).

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) Regular physical activity (yes vs. no), BMI (≤30 vs. >30 kg/m^2), smoking (no vs. current/former) and alcohol drinks/week (≤6 vs. >6). No differences in MCI between groups, overlapping 95% CIs (exact estimates not given).
Mortality					
Cole-Hunter et al. (2022)	Denmark	Danish Nurse Cohort, on 24,994 female nurses aged 44+ years at 1993/1999 recruitment. Longitudinal analysis with mean follow-up of 17.4 years.	Road traffic noise (Lden) with residential history, calculated as 5-year and 23-year means.	All-cause mortality	(0) No difference by BMI. **HR with obesity:** 1.13 (0.96, 1.33), **HR with normal BMI:** 1.07 (1.01, 1.13); p-int = 0.5068.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	CVD and all-cause mortality	Comparing BMI (<30 vs. ≥30 kg/m^2), current smoking (no vs. yes), physical activity (≥MET vs. <MET 600 min/w), fruit and vegetable consumption (high vs. low), sleep duration 7-8hr vs. <7hr/≥8hr. (+) For **all-cause mortality, HR for BMI <30:** 1.08 (1.04, 1.13), **HR BMI ≥30:** 1.06 (0.99, 1.12); p-int < 0.001. (+) **HR high fruit and veg**: 1.04 (1.00, 1.09) **HR low fruit and veg:** 1.14 (1.08, 1.20); p-int = 0.007. (+) **HR 7-8 hr sleep:** 1.05 (1.00, 1.09), **HR <7hr/≥8hr sleep:** 1.13 (1.07, 1.19) for <7hr/≥8hr; p-int = 0.022. (0) No difference in CVD mortality between groups (p-int > 0.545). Per 10 dB Lden road traffic noise.

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Thacher et al. (2020)	Copenhagen and Aarhus, Denmark	Diet, Cancer and Health cohort of 52,758 Danish born persons aged 50-64 years, with no history of cancer, were enrolled between 1993 and 1997 and followed until 2016 (median 19.5 years)	Road traffic noise (Lden) at most and least exposed facades, and including residential history.	All-cause and CVD mortality	(0) No difference by **smoking status (never, former, current)**, but highest risk in the current smokers. **All-cause mortality HR**: 1.08 (1.02, 1.14), 1.07 (1.02, 1.13) and 1.09 (1.05, 1.13), respectively; p-int = 0.89. **CVD mortality HR:** 1.03 (0.91, 1.18), 1.11 (1.00, 1.24) and 1.17 (1.09, 1.27) respectively; p-int = 0.23. Per IQR LdenMax.

In Key findings:
'p-int' refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups

3.5.1 Cardiometabolic disease

The Diet, Cancer and Health cohort study by Sørensen et al. (2012), described in 3.2.1, included over 57000 adults between the ages of 50 and 64 years at enrolment to study road traffic noise exposure in relation to MI incidence. In terms of lifestyle factors, the study tested whether the association differed with smoking status. There was some evidence of difference between groups, though the pattern was mixed with higher risk in the never and current smokers but not the former smokers. Specifically, the IRRs were 1.24 (1.05, 1.47) per 10 dB for never smokers, 0.99 (0.85, 1.15) for former smokers and 1.14 (1.02, 1.27) for current smokers, p-int = 0.11.

Most other studies on potential effect modification of noise-CVD effects by lifestyle did not see obvious difference between groups. The case-control study by Selander et al. (2009) in Stockholm County, on road traffic noise and incident myocardial infarction and described in section 3.2.1, explored a number of lifestyle factors. These included smoking (never, former, 1-10 g tobacco/day, 11-20g tobacco/day, >20 g tobacco/day), physical activity (yes, no), BMI (<27 kg/m^2, >27 kg/m^2) and job strain (no, yes). While none of the factors showed statistically significant differences, based on overlapping 95% confidence intervals in the graphical representation, there was an indication of higher risk of incident MI in former smokers (exact ORs and p-values not provided).

The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342,566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline and followed for a median of 9 years. Lifestyle factors explored in terms of effect modification included BMI (<30 kg/m^2, ≥30 kg/m^2), current smoking (no, yes), physical activity (≥MET 600 min/w, <MET 600 min/w), fruit and vegetable consumption (high, low) and sleep duration (7-8 hr, <7hr/≥8hr). For all lifestyle factors there was no sign of difference in stroke incidence between groups, except for a tendency for higher HR in those sleeping on average less or more than the normal range: 1.03 (0.96, 1.11) for 7-8 hr vs. 1.13 (1.03, 1.24) for <7hr/≥8hr per 10 dB Lden, p-int = 0.129).

The study using the Stockholm County CEANS cohort by Pyko et al. (2019), described in section 3.2.1, investigating source specific transportation noise in relation to several CVD outcomes specifically explored whether the association between road traffic noise and IHD incidence was influenced by lifestyle. The lifestyle factors included smoking (current, former, never), physical activity (sedentary, moderate, regular) and alcohol consumption (daily, weekly, seldom, never). For all lifestyle factors, there was no significant difference between groups for the associations between road traffic noise on IHD incidence, with p-int > 0.34 (exact HRs not provided).

3.5.2 Mental health

The German Heinz Nixdorf Recall (HNR) study by Orban et al. (2016), described in 3.3.2, studied road traffic noise in relation to depressive symptoms. Though not strictly a lifestyle factor, the authors also investigated potential differences in depressive symptoms by sleep, specifically comparing individuals with vs. without insomnia. They found a higher and significant association in the group indicating insomnia in relation to road traffic noise Lden >55 vs. <= 55 dB. The difference between groups, however, was not significant (RR: 1.62 [1.01, 2.59] in those with insomnia vs. 1.21 [0.94, 1.57] in those without).

3.5.3 Cognition

Three studies on transportation noise and cognition suggest little or no difference in associations by lifestyle. First, the cross-sectional analysis in the Heinz Nixdorf Recall study (2006–2008), a population-based study in the Ruhr area of Germany described in 3.1.2, evaluated cognitive performance in relation to traffic noise in 4086 participants using six tests (Tzivian et al., 2016a). In the full study population, an association was only found between road traffic noise Lden above the 60 dB threshold

and global cognitive score. To investigate effect modification by lifestyle, the authors produced models stratified by regular physical activity (yes, no), BMI (≤30, >30 kg/m^2), smoking (no, current/former) and alcohol drinks/week (≤6, >6). Across all lifestyle factors, no differences in global cognitive score between groups were found as indicated by the overlapping 95% confidence intervals (exact estimates not given). This same cohort was used to study the cross-sectional association between road traffic noise and mild cognitive impairment (Tzivian et al., 2016b). In the full study population, a significant association was found for both Lden and Lnight above the thresholds. Similar to their first study, the authors produced models stratified by regular physical activity (yes, no), BMI (≤30, >30 kg/m^2), smoking (no, current/former) and alcohol drinks/week (≤6, >6) to evaluate effect modification by lifestyle. Across all lifestyle factors, again no differences in mild cognitive impairment between groups were found (exact estimates not given).

The other study on cognition was the Swedish National study on Aging and Care in Kungsholmen (SNAC-K) study by Wu et al. (2024). Described in section 3.1.4, this study looked at the influence of lifestyle factors on the associations between source-specific transportation noise and cognitive function in older adults. Specifically, they stratified the study population by physical activity (no to mild, high) and on smoking status (ever, never, current). None of the transportation noise sources were associated with decline in global cognition score when stratified by physical activity, with p-int = 0.628, 0.689, and 0.236 respectively for road traffic, aircraft and railway noise. There were also no differences based on smoking status (p-int = 0.974, 0.746 and 0.337 for road traffic, aircraft and railway noise). The same pattern of no difference between groups was observed for cognitive impairment, no dementia (CIND) with all p-int > 0.14. The only suggestion of a difference between groups was indicated by the elevated HR of 1.96 (1.02, 3.76) per 10 dB aircraft noise in relation to CIND incidence in current smokers.

3.5.4 Mortality

Three large studies on mortality had data to investigate effect modification by lifestyle factors. The UK Biobank study by Hao et al. (2022), described in 3.1.1, studied the following lifestyle factors an whether they modify road traffic noise associations on CVD and all-cause mortality: BMI (<30 kg/m^2, ≥30 kg/m^2), current smoking (no, yes), physical activity (≥MET 600 min/w, <MET 600 min/w), fruit and vegetable consumption (high, low) and sleep duration (7-8 hr, <7hr/≥8hr). For CVD mortality, the authors found that these lifestyle factors did not modify the association with road traffic noise, with p-int > 0.545. There was, however, effect modification for all-cause mortality and several of the lifestyle factors. Specifically, there was a difference for BMI, fruit and vegetable consumption and sleep duration. For BMI the HRs were higher in those with lower BMI: 1.08 (1.04, 1.13) for <30 kg/m^2 vs. 1.06 (0.99, 1.12) ≥30 kg/m^2 per 10 dB Lden, p-int < 0.001. Meanwhile, the HRs were lower for those consuming more fruit and vegetables: 1.04 (1.00, 1.09) for high vs. 1.14 (1.08, 1.20) for low consumption per 10 dB Lden, p-int = 0.007. Finally, the HRs were lower in those with a recommended adult sleep duration: 1.05 (1.00, 1.09) for 7-8 hr vs. 1.13 (1.07, 1.19) for <7hr/≥8hr per 10 dB Lden road traffic noise, p-int = 0.022.

On the other hand, the Danish Nurses cohort study by Cole-Hunter et al. (2022) (section 3.1.1), found no statistical difference in road traffic noise and all-cause mortality between the groups of participants stratified by BMI, with HR of 1.13 (0.96, 1.33) per 10 dB Lden for those with obesity vs. 1.07 (1.01, 1.13) for those with normal BMI (p-int = 0.5068). The Diet, Cancer and Health cohort including 52,758 Danish born persons aged 50-64 years, with no history of cancer also found no difference in the noise-mortality associations by lifestyle (Thacher et al., 2020) (section 3.3.6). The study used road traffic noise at the most and least exposed facades. All-cause mortality and CVD mortality were included in analyses into the potential effect modification by smoking (never, former, current). Similar HR were found when using either the most or least exposed facades, with slightly stronger effects in relation to the most exposed facade. Overall, the effects did not differ significantly by smoking status but were highest in the current smokers. For all-cause mortality, the HRs were 1.08 (1.02, 1.14) per IQR LdenMax

for never smokers, 1.07 (1.02, 1.13) for former smokers and 1.09 (1.05, 1.13) for current smokers (p-int = 0.89). For CVD mortality, the HRs were 1.03 (0.91, 1.18) for never smokers, 1.11 (1.00, 1.24) for former smokers and 1.17 (1.09, 1.27) for current smokers (p-int = 0.23).

3.6 Genetic predisposition

This section focuses on studies that have specifically explored genetic predisposition or family history of diseases such as CVD and cognitive impairment that may influence susceptibility (Table 3.6).

Table 3.6 Summary table of studies on genetic predisposition

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Cardiometabolic disease					
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	Stroke incidence	(0) No difference by family history of CVD. **HR no history:** 1.05 (0.96, 1.15), **HR yes history:** 1.08 (1.01, 1.16); p-int = 0.613. Per 10 dB Lden.
Eze et al. (2017)	Switzerland	SAPALDIA study including 3350 adults (29–81 years old) who completed the first (SAP2: 2001/2) and second (SAP3: 2010/11) SAPALDIA follow-up surveys, linear mixed models	Nighttime road traffic, railway and aircraft noise, most exposed façade (Lnight)	Glycosylated haemoglobin (HbA1c)	(+) Positive association between RTN and change in HbA1c in non-movers, significantly stronger in diabetics with genetic risk of circadian rhythm disruption (p-int = 0.001).
Cognition					
Tzivian et al. (2016a)	Three cities (Bochum, Essen, and Mülheim/Ruhr) in Ruhr area, Germany	Population-based Heinz Nixdorf Recall study (2006–2008), second evaluation including 4086 adults (mean age 64 years), cross-sectional	Road traffic noise (Lden and Lnight) at most exposed façade. Used as continuous variable with threshold at 60 dB Lden/55 dB Lnight	Cognition performance tests (Verbal fluency, Labryinth, Immediate recall, Delayed recall, Global cognitive score, Clock drawing)	(0) No difference in global cognitive score by APOE genotype (APOE-ε4 carrier vs. non-carrier), overlapping 95% CIs (exact estimates not given).

Citation	Study area	Population / study design	Exposure	Outcome	Key findings
Tzivian et al. (2016b)	Same as above	Same as above	Same as above	Mild cognitive impairment (MCI)	(0) No difference in MCI by APOE genotype (APOE-ε4 carrier vs. non-carrier), overlapping 95% CIs (exact estimates not given).
Mortality					
Hao et al. (2022)	United Kingdom	UK Biobank study, including 342,566 participants 40-69 years at recruitment (2006-2010), and free of CVD at baseline. Longitudinal analysis with median 9 years follow-up	Road traffic noise (Lden)	CVD and all-cause mortality	(~) No difference by family history of CVD, though tendency for higher risk with history. **CVD mortality HR no history:** 1.07 (0.94, 1.21), **HR history:** 1.16 (1.05, 1.28); p-int = 0.275. (0) **All-cause mortality HR no history:** 1.07 (1.02, 1.12), **HR history:** 1.09 (1.04, 1.14); p-int = 0.559. Per 10 dB Lden.

In Key findings:
‘p-int’ refers to p-value for interaction, with p ≤0.05 taken to indicate a statistically significant difference between groups
95% confidence intervals in brackets
(+) clear difference between groups, statistically significant
(~) indication of some difference between groups, not statistically significant
(0) no difference between groups

3.6.1 Cardiometabolic disease

The UK Biobank study by Hao et al. (2022), described in 3.1.1, included 342,566 participants 40-69 years at recruitment (2006-2010), free of CVD at baseline and followed for a median of 9 years. For the incident CVD outcomes, the main analysis showed only showed a borderline significant association for road traffic noise and incident stroke that attenuated after adjusting for $PM_{2.5}$. The authors also investigated potential differences in stroke incidence based on family history of CVD (no vs. yes), finding no evidence of effect modification (HR of 1.05 (0.96, 1.15) per 10 dB Lden road traffic for no history vs. 1.08 (1.01, 1.16) for history of CVD noise, p-int = 0.613).

With the Swiss SAPALDIA study, including 3350 adults (29–81 years old) who completed the first (SAP2: 2001/2) and second (SAP3: 2010/11) follow-up surveys, Eze et al. (2017) studied nighttime road traffic noise in relation to 8-year change in glycosylated haemoglobin (ΔHbA1c) which is a marker of diabetes. They further investigated the modification of this relationship by a genetic risk score for circadian rhythm disruption (comprised of six common circadian-related MTNR1B variants). They reported a positive association between Lnight and change in HbA1c in non-movers that was significantly stronger among diabetic individuals with the genetic predisposition for circadian rhythm disruption (p-int = 0.001).

3.6.2 Cognition

The cross-sectional analysis in the Heinz Nixdorf Recall study (2006–2008), a population-based study in the Ruhr area of Germany described in 3.1.2, evaluated cognitive performance in relation to traffic noise in 4086 participants with a suite of six tests (Tzivian et al., 2016a). In the full study population, an association was only found between road traffic noise Lden above the 60 dB threshold and global cognitive score. The authors also investigated whether there was difference based on APOE genotype (APOE-ε4 carrier, non-carrier), previously reported to increase the risk for Alzheimer's disease. Their stratified analyses, however, indicated no difference global cognitive score by genetic risk, based overlapping 95% confidence intervals (exact estimates not given). Tzivian et al. (2016b) used the same population was used to evaluate the association between mild cognitive impairment and road traffic noise. In the full study population, a significant association was found for both Lden and Lnight above the thresholds. Regarding effect modification by APOE genotype (APOE-ε4 carrier, non-carrier), their stratified analyses indicated higher risk of mild cognitive impairment in the carrier vs. non-carrier subsets, though not statistically different as per the overlapping 95% confidence intervals (exact estimates not given).

3.6.3 Mortality

Only the UK Biobank study by Hao et al. (2022), described in 3.1.1, investigated potential differences in risk of CVD and all-cause mortality due to genetic predisposition to disease. Here they used family history of CVD (no, yes). For both outcomes there were indications of higher risk in the group with a family history of CVD, however the differences were not significant as indicated by the overlapping 95% confidence intervals and p-value for interaction. For CVD mortality the HRs were 1.07(0.94, 1.21) per 10 dB Lden road traffic for no history vs. 1.16(1.05, 1.28) for family history, p-int = 0.275. For all-cause mortality the HRs were 1.07(1.02, 1.12) for no history vs. 1.09(1.04, 1.14) for history, p-int = 0.559.

4 Situational factors - socioeconomic status

This section explores the situational factors that contribute to vulnerability. Lower housing prices often correspond with higher noise levels (Szczepańska et al., 2020) and thus people with higher material deprivation index may more likely to be exposed to transportation noise. The harmful intersection of hazards, exposure and vulnerability on health is elaborated in the 2018 report by the European

Environment Agency (EEA) "Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe" (EEA, 2018). In short, unfavourable environmental conditions, in particular noise exposure in residential areas, substantially contributes to social inequality within Europe. This can further contribute to ill-health, poor wellbeing and sleep deprivation, in combination yielding lower work performance and thereby widening the gap between those with financial resources versus those without. Unfavourable environmental conditions may also affect development of children and thus be "inherited" to the next generation.

Most studies report that lower SES or higher deprivation is associated with greater exposure to road, railway, or aircraft noise in European cities and regions. A review of eight studies published between 2010 and 2017 on social inequalities in environmental noise exposure in the WHO European Region concluded that there was a trend that groups with lower socioeconomic position based on material deprivation and deprivation indices showed higher environmental noise exposures (Dreger et al., 2019). However, the situation may be complex depending on the urban structure and residential preferences. For instance, in a nationwide Dutch study, not included in the review above, exceeding of the road traffic noise threshold of 53 dB was observed in 46% of neighbourhoods and in general vulnerable, marginalized, and less privileged neighbourhoods had higher noise levels (Hayward and Helbich, 2024). Conversely, employment rate was positively correlated with noise exposure in this study. In a German study from Hamburg people with lower SES and younger age were more likely to be affected by noise (Von Szombathely, 2018). In Marseilles, France, the highest noise exposure was found in intermediate deprivation areas, not the most deprived (Bocquier et al., 2013); and in Paris, higher noise exposure was observed in advantaged neighbourhoods (Havard et al., 2011). In Switzerland, populations highly exposed to road and railway noise (Lden>55 dB, intermittency ratio>80%) had a lower socioeconomic position and education than the total population, whereas it was the other way around for people highly exposed to aircraft noise (Heritier et al., 2017).

In summary, there is a trend that lower SES increases the risk for noise exposure, although some of the noisy areas in city centres may be also very attractive for residency and thus also attract people with high SES and/or high occupational position. It is conceivable that in this situation, noise mitigation like noise barriers, low noise pavements or soundproof windows are implemented with a higher chance. Strikingly, we did not identify any European study that directly mapped noise mitigation measures against SES or deprivation. Thus, although it is plausible that noise burden is unequal distributed and that there are hints that disadvantaged groups likely have inferior building quality and less effective noise mitigation, this topic remains a clear research gap. Further studies should address the observed trend towards widening of inequalities across European regions owed to exposure to transportation noise and air pollution (German et al., 2018).

5 Evaluation of the lower effect threshold for vulnerable groups

Table 5.1 overviews the studies in Chapter 3, indicating the noise exposure reference level if available per study. Overall, 86% of the included studies that mention a reference used noise level at or below the relevant WHO Environmental Noise Guidelines (WHO, 2018). The table also shows the evidence for effect modification per study, indicating the highest level of evidence across all themes, outcomes and specific vulnerabilities it explored. For example, if any of these combinations showed a statistically significant difference between groups, the evidence of effect modification column is marked as (+). Across the studies, 45% had at least one combination where statistically significant effect modification was reported, followed by 38% that showed non-statistically significant increased risk in one group compared to another. Only 17% of studies included in this report showed no evidence of effect modification at all.

Taken together this summary suggests that the current environmental noise guidelines are not sufficient for the protection of vulnerable populations, with many of studies showing or indicating

differences between groups having reference levels below the relevant threshold in the ENG guidelines. However, we did not find studies providing evidence on whether the thresholds differ between vulnerable groups and the healthy population. This gap remains to be addressed.

Table 5.1 Overview of reference noise levels and evidence of effect modification

Citation	Study area	Exposure	Reference [or descriptive statistic][1]	Evidence of effect modification[2]
Andersen et al. (2018)	Denmark	Road traffic noise (Lden)	< 48 dB [mean 52.7, SD 8.2]	(+)
Bartoskova Polcrova et al. (2025)	Brno, Czech Republic	Combined road traffic, railway and aircraft noise (Lden)	< 51 dB	(+)
Baudin et al. (2021)	Around airports in France	Aircraft noise (Lden)	< 50 dB	(+)
Cole-Hunter et al. (2022)	Denmark	Road traffic noise (Lden)	no obvious reference [mean 52.7, SD 7.9]	(~)
Dzhambov et al. (2023)	Sofia, Bulgaria	Road traffic, railway and aircraft noise (Lden)	< 50 dB	(+)
Eze et al. (2017)	Switzerland	Road traffic noise (Lnight)	< 25 dB	(+)
Gong et al. (2024)	Around 4 airports London Heathrow, London Gatwick, Birmingham and Manchester in United Kingdom	Aircraft noise contours (Lnight)	< 45 dB	(~)
Halonen et al. (2014)	Finland	Road traffic noise (Lden)	≤ 45 dB	(+)
Halonen et al. (2015)	Greater London, United Kingdom	Road traffic noise (LAeq16 and Lnight)	< 55 dB	(0)
Hao et al. (2022)	United Kingdom	Road traffic noise (Lden)	[range 53.5 - 57.0 dB]	(+)
Klompmaker et al. (2019)	Netherlands	Road traffic and railway noise (Lden)	[p5 road traffic: 45.4 dB; p5 railway: 29.0 dB]	(0)
Klompmaker et al. (2021)	Netherlands	Road traffic noise (Lden)	[road traffic: median 53.7, IQR 7.5; railway: 30.7, 9.4]	(~)

Citation	Study area	Exposure	Reference [or descriptive statistic][1]	Evidence of effect modification[2]
Kodji et al. (2023)	Around 3 airports Paris-Charles de Gaulle, Lyon Saint-Exupéry and Toulouse-Blagnac in France	Aircraft noise (Lden and LAeq24h)	[p5 44 dB]	(~)
Mutz et al. (2021)	United Kingdom	Road traffic noise (Lden)	[range: 51.6 - 89.3 dB]	(0)
Olbrich et al. (2023)	Frankfurt, Germany	Aircraft (Lden)	< 35 dB	n/a
Orban et al. (2016)	Ruhr area, Germany	Road traffic noise (Lden and Lnight)	≤ 55 dB	(~)
Pyko et al. (2019)	Stockholm County, Sweden	Road traffic, railway and aircraft noise (Lden)	< 45 dB	(+)
Röösli et al. (2014)	Basel, Switzerland	Road traffic noise (Lnight)	< 30 dB	(+)
Selander et al. (2009)	Stockholm County, Sweden	Road traffic noise (LAeq,24 above 50 dBA vs. below)	< 50 dB	(~)
Sørensen et al. (2012)	Copenhagen and Aarhus, Denmark	Road traffic noise (Lden)	< 42 dB	(~)
Sørensen et al. (2021)	Denmark	Road traffic noise (Lden)	< 45(40) dB Lden Max(Min)	(+)
Sørensen et al. (2023)	Denmark	Road traffic and railway noise (Lden)	road traffic: < 40(37) dB Lden Max(Min); railway: <35 dB Lden	(~)
Sørensen et al. (2024)	Denmark	Road traffic noise (Lden)	< 35 dB	(+)
Thacher et al. (2020)	Copenhagen and Aarhus, Denmark	Road traffic noise (Lden)	< 35 dB	(~)
Tonne et al. (2016)	Greater London, United Kingdom	Road traffic noise (LAeq16)	[p25 55 dB]	n/a
Tzivian et al. (2016a)	Ruhr area, Germany	Road traffic noise (Lden and Lnight)	[min 0 dB, p25 46.7(38.2) dB Lden (Lnight)]	(0)
Tzivian et al. (2016b)	Ruhr area, Germany	Road traffic noise (Lden and Lnight)	[min 0 dB, p25 46.7(38.2) dB Lden (Lnight)]	(0)

Citation	Study area	Exposure	Reference [or descriptive statistic][1]	Evidence of effect modification[2]
Vienneau et al. (2022)	Switzerland	Road traffic noise, railway, aircraft (Lden)	road traffic: <35 dB; aircraft/railway: <30 dB	(+)
Vienneau et al. (2023)	Switzerland	Total transportation noise (road traffic, railway, aircraft) (Lden)	< 35 dB	(+)
Wu et al. (2024)	Sweden	Road traffic, railway and aircraft noise (Lden)	40 dB	(~)
Zhang et al. (2024)	United Kingdom	Road traffic noise (Lden)	[p10 52.1 dB]	(~)

1. Shaded if indicated threshold is at or below the WHO END guideline
2. Highest level of evidence of effect modification for at least 1 theme/outcome/vulnerability combination. Based on: (+) clear difference between groups, statistically significant which is here shaded, (~) indication of some difference between groups, not statistically significant, and (0) no difference between groups.

6 Protection of vulnerable groups - policy implications

This review gives an overview about studies investigating whether certain population groups are particularly vulnerable to the impact of noise exposure. The studies examined different factors that might make someone more vulnerable, such as having an existing illness, being older, sex or gender, lifestyle habits and behaviours, genetic factors, or social and economic circumstances. Many studies identified significant effect modification for at least one vulnerability factor (Table 5). Within factor, however, there was no clear pattern of higher risk in one group vs. another. Overall, this suggests that a person's vulnerability to noise is mainly linked to their underlying risk of disease in general. In other words, the higher the baseline health risk, the larger the health impact from transportation noise. This implies:

- People with pre-existing diseases such as cardiometabolic conditions, mental health problems and sleep disturbances tend to be more affected by transport-related noise, as do older adults for whom age-related susceptibility plays a role.
- For sex/gender the evidence is more mixed. The impact appears to depend on the specific health outcome. For example, health conditions that are more prevalent in men tend to show stronger associations with noise exposure in men, and the same pattern is found for women.
- Of the lifestyle related factors, smoking generally stands out as a modifiable risk factor influencing vulnerability to noise effects on health. For mortality, the evidence was mixed but suggests that BMI and diet are important.
- In addition, non-biological or situational factors such as socio-economic status can also moderate the risk of developing noise-related health conditions, since the likelihood to be exposed to transportation noise is increased.

All vulnerable groups are thus susceptible to the harmful effects of transportation noise proportional to their baseline risk. However, noise is a risk factor for everyone - even the healthy. For instance, a recent study by Wicki et al. (2025) conducted in a healthy population, demonstrated that noise exposure was linked to early indicators of cardiometabolic risk, such as elevated blood pressure, impaired glucose metabolism, and vascular changes. Thus, while it is clear noise exacerbates pre-existing conditions, this study highlights subclinical effects of noise also in healthy populations. In this light, policy should address susceptibility in a general sense to ensure and keep the population healthy. At the same time, policy makers have an obligation to reduce injustice and inequity as much as possible, to reduce exposure and the burden of disease for vulnerable groups. This is particularly relevant for the vulnerabilities in this review on which policy action can be impactful, including for patient populations and those with genetic predisposition, on lifestyle and behaviours and the situational factors that can be bettered through equitable policy.

7 List of abbreviations

Abbreviation	Name	Reference
AR	Absolute risk	
%BF	% body fat	
BMI	Body mass index	
CHD	Coronary heart disease	
CI	confidence intervals	
CIND	Cognitive impairment, no dementia	
COPD	Chronic obstructive pulmonary disease	
CVD	Cardiovascular disease	
dB	decibel	
EEA	European Environment Agency	www.eea.europa.eu
GCS	Global cognition score	
HR	Hazard ratio	
HF	Heart failure	
HS	Haemorrhagic stroke	
IHD	Ischemic heart disease	
IQR	Interquartile range	
IRR	Incidence rate ratio	
IS	Ischemic stroke	
Lden	Average day-evening-night noise level (with 5 dB evening and 10 dB night penalty), in dB	
LdenMax	Lden at maximum exposed façade	
LdenMin	Lden at minimum exposed façade	
Lnight	Average nighttime noise level in dB	
MCI	Mild cognitive impairment	
MI	Myocardial infarction	
Non-RD	Non-respiratory disease	
OR	Odds ratio	
p-int	P value for interaction	
p-trend	P value for trend	
PSRH	Poor self-rated health	
RD	Respiratory disease	
RR	Relative risk	
RTN	Road traffic noise	
SES	Socioeconomic status	
SGH	Self-perceived general health	
SRHS	Self-rated health status	
VFA	Visceral fat area	
WC	Waist circumference	

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