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Transportation noise and self-rated health: Evidence from the German national cohort (NAKO)

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A B S T R A C T

Background: A large proportion of Europeans are exposed to high levels of transportation noise, which can cause physiological and psychological stress, leading to negative health impacts. Few studies have examined the association between transportation noise and self-rated health (SRH), a summary indicator of morbidity.

Objectives: We aimed to assess the associations of SRH with both annual average road traffic noise exposure and nighttime transportation noise annoyance, examine geographic differences, evaluate potential effect modification and interaction by sex, and investigate whether annoyance mediates the relationship between road traffic noise and self-rated health.

Methods: Using NAKO baseline data (n = 174,956), we implemented a cross-sectional study using logistic regression to analyze associations of road traffic noise ≥55 dB(A) Lden and nighttime transportation noise annoyance with poor SRH, adjusting for relevant sociodemographic characteristics and environmental co-exposures, including air pollution and greenness. We examined geographic differences, tested for effect modification and interaction by sex, and used path analysis to assess mediation by annoyance.

Results: Road traffic noise ≥55 dB(A) (OR 1.06, 95 % CI 1.01; 1.10), and moderate (OR 1.28, 1.23; 1.32) and strong nighttime transportation noise annoyance (OR 1.73, 1.65; 1.81) were associated with higher odds of poor SRH. Associations were similar for males and females, but varied across study regions. The path analysis revealed that road traffic noise was associated with higher odds of poor SRH indirectly via nighttime transportation noise annoyance (indirect effect).

Conclusions: In our study, nighttime transportation noise annoyance was more strongly and consistently associated with poor SRH than road traffic noise. Reducing both transportation noise and related annoyance could help protect population health.

1. Background

Exposure to noise from road, rail, and air transportation is an important environmental health risk (World Health Organization Regional Office for Europe, 2011; European Environment Agency, 2025a). Transportation noise may cause psychological and physiological distress, leading to the secretion of stress hormones and increased blood pressure, which can negatively affect cardiovascular and metabolic health, especially with long-term exposure (Arregi et al., 2024; Rylander, 2004). One of the most common types of distress in response to transportation noise is annoyance, characterized by feeling bothered or disturbed, which has also been linked with a variety of health impacts (Clark et al., 2021; Senerth et al., 2024). At night, transportation noise can disturb sleep and reduce sleep quality, affecting health-related biological functions (such as cardiovascular, endocrine, and metabolic functions), mental health, academic and work performance, and social relationships (Arregi et al., 2024; Halperin, 2014). Beyond its direct physiological and psychological effects, exposure to transportation noise at home may indirectly worsen health by constraining restorative aspects of the home environment that otherwise would have been health-promoting (von Lindern et al., 2016).

According to the European Environment Agency (EEA), in 2021, over 112 million people in the region (more than 20 % of the population) were exposed to transportation noise above the Environmental Noise Directive (END) threshold of 55 dB(A), with road traffic noise being the main source (European Environment Agency, 2025b). In Germany, 26 % of the population is exposed to transportation noise levels above this threshold (European Environment Agency, 2025b). The EEA estimates that transportation noise contributes to 66,000 premature deaths and 1.3 million healthy years of life lost annually in Europe, with 12,300 premature deaths and 310 years of healthy life lost per 100,000 people per year in Germany alone (European Environment Agency, 2025b).

Despite longstanding recognition of transportation noise as an important health risk (Babisch, 2006; Stansfeld and Matheson, 2003), the literature examining the relationship between transportation noise and self-rated health (SRH), a widely used and holistic indicator of population health and well-being, remains limited. SRH, typically assessed with a single survey question on a Likert scale, provides a useful summary of morbidity while also capturing a person's subjective experience of their own health and wellbeing (Idler and Benyamini, 1997; Jylhä, 2009). SRH is also a predictor of quality of life and mortality (Idler and Benyamini, 1997; Jylhä, 2009). While several studies have found and reported associations between objectively measured road traffic noise or subjectively reported transportation noise annoyance and worse SRH (von Lindern et al., 2016; Baudin et al., 2021; Brink, 2011; Halonen et al., 2014; Kodji et al., 2023; Riedel et al., 2015; Riedel et al., 2017; Totouom et al., 2023), others have not (Dzhambov et al., 2023; Klompmaker et al., 2019; Kodji et al., 2024; Mutz et al., 2021; Putrik et al., 2015). Only two very large studies (sample size >100,000) have examined objectively measured road traffic noise and SRH, both reporting null results (Klompmaker et al., 2019; Mutz et al., 2021). More than half of the studies on transportation noise annoyance and SRH have focused solely on air or rail transportation noise (Baudin et al., 2021; Kodji et al., 2023, 2024; Riedel et al., 2015, 2017; Putrik et al., 2015). Evidence of effect modification by sex is sparse, with only two studies reporting associations between objectively measured road traffic noise (Halonen et al., 2014) and subjectively reported air traffic noise annoyance (Baudin et al., 2021) in men but not in women. Transportation noise annoyance may also play an important mediating role between transportation noise exposure and the corresponding stress response, which may lead to poor health outcomes (Riedel et al., 2015), underscoring the importance of considering both objective measures of traffic noise and subjective measures of annoyance. However, only one known study has assessed objectively measured road traffic noise and transportation noise annoyance separately and in combination on SRH, but did not perform a formal mediation analysis (Riedel et al., 2015). Road traffic is also a major source of ambient air pollution, including fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2), which have been linked to poorer SRH and other adverse health outcomes (Klompmaker et al., 2019). In addition, greater residential greenness, often quantified using the Normalized Difference Vegetation Index (NDVI), has been associated with better perceived health and lower risks of several chronic conditions (Rhew et al., 2011). Because lower levels of greenness and higher levels of air pollution tend to co-occur with road traffic noise, they may confound or modify associations between noise exposure and health (Poulsen et al., 2023). Two of the identified existing similar studies (Dzhambov et al., 2023; Mutz et al., 2021) have taken NDVI and air pollution into account when assessing the relationship between road traffic noise and SRH, and neither of them found that road traffic noise had a significant association with SRH in multi-exposure models.

To address the identified gaps in the evidence, we investigated the associations of annual average road traffic noise exposure and subjectively reported nighttime transportation noise annoyance with SRH in a cross-sectional study using data from the German National Cohort's (NAKO) baseline examination. Our research questions were: 1) How is exposure to higher annual average road traffic noise associated with the odds of reporting worse SRH? 2) How is nighttime transportation noise annoyance associated with the odds of reporting worse SRH? 3) Do these associations vary across study regions? 4) Does sex modify these associations? 5) Does nighttime transportation noise annoyance mediate the relationship between road traffic noise and SRH?

2. Methods

2.1. Study design and population

The NAKO is a multicenter prospective study that aims to investigate the causes of chronic diseases such as cancer, diabetes, and cardiovascular disease, and is the largest epidemiological study ever undertaken in Germany (Peters et al., 2022). Baseline data were collected from 205,415 individuals aged 19–74 years between March 2014 and September 2019 at 18 coordinated study centers in 16 study regions across Germany (Rach et al., 2025). Participants were recruited using an age- and sex-stratified sampling design which aimed to enroll 20,000 participants for each 10-year age group for the ages 20–39 years, and 53,400 participants for each 10-year age group aged 40 and above (Rach et al., 2025). Participants were identified from local registries in designated study areas and invited to participate in the NAKO by corresponding local study centers (Peters et al., 2022). Data collection involved standardized interviews, self-administered questionnaires, and medical examinations. A map of study sites can be found in Figure S1.

2.2. Measures

2.2.1. Outcome

SRH was assessed through the routinely used question, “How would you describe the state of your health, in general?” (Jylhä, 2009). Participants responded on the standard five-point Likert scale ranging from “excellent” to “poor” (Jylhä, 2009). Responses were dichotomized as “excellent,” “very good,” or “good” (referred to as “good SRH”) (0) and “fair” or “poor” (referred to as “poor SRH”) (1), as is commonly done in studies of SRH (Mackenbach et al., 2018).

2.2.2. Noise variables and co-exposures

Nighttime transportation noise annoyance was measured by asking, “How annoyed are you at night (between 10 p.m. and 6 a.m.) by noise from cars, trucks, trains, or airplanes in your bedroom when the windows are tilted or completely open?”. Participants reponded using a five-point Likert scale. Responses were grouped as: 1) not annoyed at all (scale response 1), 2) slightly or moderately annoyed (scale responses 2–3), and 3) strongly or extremely annoyed (scale responses 4–5) (Wolf et al., 2020). Though we consider nighttime transportation noise annoyance as a mediating variable in some of our analyses, we refer to it as an “exposure” throughout the manuscript, both for the sake of simplicity but also because this measure likely captures a degree of unmeasured objective exposure to nighttime transportation noise related to bedroom position relative to main streets and noisy traffic, noise proofing, window opening behavior, and window and building materials (Klæboe et al., 2004; Jakovljevic et al., 2009; Preisendörfer et al., 2022).

Road traffic noise exposure was calculated as the annual mean day-evening-night level dB(A) of 24-h ambient road traffic noise levels for the year 2017 within a 10-m buffer of each participant's residence (Staab et al., 2025). Annual day-evening-night levels (Lden) are weighted yearly averages of area-level noise, which include an added “penalty” (or weight) of 5 dB(A) for evening noise and of 10 dB(A) for nighttime noise. Data were downloaded from the central EEA data repository, the European Environment Information and Observation Network (EIONET), as 84 shapefiles delineating five Lden classes, corrected for topological errors and harmonized to a Germany-wide raster. Annual mean noise levels for each resident were initially categorized as 1) missing, as no measurement was required by the END, 2) any annual mean Lden noise level below 55 dB(A), 3) 55 to under 60 dB(A), 4) 60 to under 65 dB(A), 5) 65 to under 70 dB(A), 6) 70 to under 75 dB(A), and 7) 75 dB(A) and above. The END recommends an annual mean Lden noise level of less than 55 dB(A). In alignment with the EEA's directive, we assume that participants in areas not covered by the END are living in low-noise areas. Because of this, these levels were grouped into two categories: 1) missing (no measurement) and low noise (less than 55 dB [A]), and 2) high noise (55 dB[A] and above).

To account for other environmental characteristics related to transportation, we included three environmental co-exposures when examining the association between road traffic noise and SRH. Annual mean levels of fine particulate matter with a diameter of less than 2.5 μm ($PM_{2.5}$) and annual mean levels of nitrogen dioxide (NO_2) were measured as $\mu g/m^3$ within a 50-m buffer area surrounding each participant's place of residence, corresponding to their year of participation in the NAKO's baseline data collection (de Hoogh et al., 2025; Shen et al., 2022). We also included Terra Moderate Resolution Imaging Spectroradiometer (MODIS) normalized difference vegetation index (NDVI) averaged between March and October (“vegetation period”), developed using a mask layer to exclude water pixels (Didan, 2015). NDVI values represented averages for 1 km buffer areas surrounding participant residences for the year of participation in the NAKO baseline examination to assess neighborhood-level greenspace. Both air pollutant variables and the NDVI variable were scaled by their interquartile ranges (IQR), and we reversed the sign of the IQR-scaled NDVI variable (multiplied by -1) to generate associations per IQR decrease in NDVI (lower greenness), rather than per increase.

2.2.3. Covariates

Age was analyzed as a continuous variable. The functional form of the association between age and poor SRH was assessed by fitting multivariable logistic regression models with age parameterized using restricted cubic splines and plotting model-based predicted probabilities across age (Figure S2). We found that age had a non-linear relationship with SRH. To account for this non-linear relationship in our main analyses, we generated restricted cubic spline terms for age with knots at the 10th, 50th, and 90th percentiles of the age distribution (30, 51, and 66 years), and included all resulting spline terms as covariates in the logistic regression models. Information on participants' sex assigned at birth was gathered as a binary variable (male or female) from civil registries during the participant recruitment process and was also subsequently documented by study nurses during examination (Moreno

Velásquez et al., 2025). Marital status was reported as single, married and living with spouse, married but living separately from spouse (separated), divorced, or widowed. Level of education was defined in alignment with the United Nations Educational, Scientific and Cultural Organization (UNESCO) international standard classification of education (ISCED) for the year 2011. Migration background was defined as either the participant or one of their parents having been born in a country other than Germany. NAKO study site was included as a categorical dummy variable, with a unique value assigned to each of the 16 sites. To assess potential multicollinearity among covariates, variance inflation factors (VIFs) were calculated from linear regression models using the same predictor set as the main logistic regressions; all non-spline VIFs were below five, confirming no problematic collinearity.

All covariates and their hypothesized relationship with the exposures and outcome are illustrated in a directed acyclic graph (DAG, Figure S3). We did not include any covariates related to health behaviors, mental health status, or objectively measured health status, as these characteristics are theorized to be captured within an individual's summarized assessment of their own health in the outcome variable SRH (Jylhä, 2009). As demonstrated in the DAG, these characteristics also lie along the theorized causal pathway between transportation noise exposure and SRH, as the psychological and physiological stress caused by transportation noise exposure and related noise annoyance may affect health behaviors and/or health status which in turn affect an individual's perception of their health, and therefore controlling for these variables could mask the hypothesized relationship between noise and SRH.

2.2.4. Missingness and imputation

We included all participants with complete outcome and exposure data (N = 174,956). To retain as many participants as possible in our analysis, we performed a single imputation for all missing covariate and co-exposure data, imputing the median for continuous covariates and the mode for categorical covariates, as is recommended for statistical analysis when using data for the NAKO (Kuss et al., 2022).

2.3. Statistical analysis

Descriptive statistics were calculated for all variables, including counts, proportions, means, and standard deviations. Associations between categorical variables were assessed using Chi-squared tests and Cramer's V. Spearman's correlations were used for continuous variable pairs and for continuous and binary variable pairs. One-way analysis of variance (ANOVA) and η^2 (Eta-squared) were used for continuous and multi-category variable pairs.

Logistic regression was used to estimate associations between exposures and the odds of poor SRH, expressed as odds ratios (ORs) with 95 % confidence intervals (CIs). We used two covariate sets: a minimum set and a main set. Our minimum covariate set controlled for age and sex. Our main covariate set controlled for age, sex, marital status, level of education, migration background, and NAKO study site as potential confounders. As we cannot assume an ordinal relationship between nighttime transportation noise annoyance and SRH, we treated this exposure variable as categorical. We implemented three sets of logistic regression models. The first set ("noise-only minimum model") incorporated the minimum covariate set and excluded co-exposures. The second set ("noise-only main model") incorporated the main covariate set and excluded co-exposures. The third set ("multi-exposure main model") incorporated the main covariate set and all three co-exposures. Within each of the three sets, we ran three models: a model for objectively assessed road traffic noise, a model for nighttime transportation noise annoyance, and a model that included both. Effect modification by sex was assessed via stratification and multiplicative interaction terms within our multi-exposure main models. We replicated our multi-exposure main models stratified by NAKO study site to explore geographic variation in associations separately for road traffic noise and for nighttime transportation noise annoyance.

We conducted a path analysis to test whether nighttime transportation noise annoyance mediates the association between road traffic noise (≥55 dB(A)) and poor SRH. The model was adjusted for all covariates and co-exposures. In total, 72 regression paths were explicitly specified, primarily for covariate adjustment, including fixed effects for study site (16 categories), marital status (5 categories), and education (9 categories). The model comprised two structural equations (mediator and outcome equations) and did not include residual covariances beyond those required for estimation. This specification resulted in a just-identified path model with zero degrees of freedom (df = 0), due to the explicit estimation of all regression paths required to adjust for covariates and co-exposures. Model parameters were estimated using diagonally weighted least squares (DWLS), which is appropriate for ordinal outcomes, yielding unstandardized probit-scale coefficients. These reflect effects on the underlying continuous response assumed by the probit model. Statistical inference for direct (a: noise → annoyance; b: annoyance → SRH; c': direct noise → SRH), indirect (a × b; noise → annoyance → SRH), and total (c' + indirect) effects was based on 95 % percentile bootstrap confidence intervals obtained from 1000 resamples. Hu and Bentler (1999) recommend a Comparative Fit Index (CFI) or Tucker–Lewis Index (TLI) ≥ 0.95 in combination with a root mean square error of approximation (RMSEA) ≤ 0.06 as evidence of good fit for over-identified models (Hu and Bentler, 1999). These benchmarks do not apply in the present analysis because the model was just-identified (df = 0), and DWLS estimation further tends to overestimate fit indices in small-df models. Consequently, any resulting perfect fit indices are a mathematical consequence of the model being just-identified (df = 0) rather than evidence of substantive fit, and should not be interpreted as tests of model adequacy.

We conducted several sensitivity analyses. We implemented our multi-exposure main models while restricting the included observations to individuals who had lived in their residence for at least five years, to assess whether any differences in outcome by duration of residence could be detected. We implemented our multi-exposure main models while restricting our sample to those residing within areas where noise measurement is mandated by the END. We used alternate exposure variables within our multi-exposure main models, allowing us to see how results vary when the annual mean traffic noise variable is included in its original form as a multi-category variable, and to examine the association between moderate/strong annoyance and extreme annoyance with SRH, compared with no annoyance/slight annoyance. We also implemented our multi-exposure main model for both noise variables separately using multinomial logistic regression with an alternate outcome variable, where participants were grouped as reporting 1) very good or excellent, 2) good, or 3) fair or poor health. We performed an additive interaction analysis to assess whether the combination of reporting any nighttime transportation noise annoyance (ordinal scale

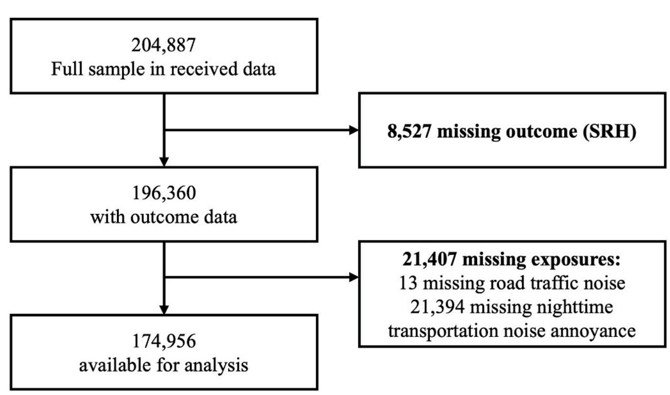

Fig. 1. STROBE flow diagram showing the reasons for excluding participants from the study.

Table 1
Descriptive statistics for the full sample and stratified by SRH status, including means and standard deviations for age, and counts and column percentages for all other variables.

	Full sample	Good SRH	Poor SRH
	N (%) or mean ± SD	N (%) or mean ± SD	N (%) or mean ± SD
Sample	174,956	156,958 (89.7)	17,998 (10.3)
SRH			
Excellent	6888 (3.9)	6888 (4.4)	0 (0.0)
Very good	54,906 (31.4)	54,906 (35.0)	0 (0.0)
Good	95,164 (54.4)	95,164 (60.6)	0 (0.0)
Fair	16,663 (9.5)	0 (0.0)	16,663 (92.6)
Poor	1335 (0.8)	0 (0.0)	1335 (7.4)
Annual mean road traffic noise			
Low noise (<55 dB(A))	136,624 (78.1)	122,705 (78.2)	13,919 (77.3)
High noise (≥55 dB(A))	38,332 (21.9)	34,253 (21.8)	4079 (22.7)
Nighttime transportation noise annoyance			
Not at all annoyed	108,675 (62.1)	89,732 (62.9)	9943 (55.3)
Slightly/moderately annoyed	48,001 (27.4)	42,681 (27.2)	5320 (29.6)
Strongly/extremely annoyed	18,280 (10.5)	15,545 (9.9)	2735 (15.2)
Age in years	48.8 ± 12.7	48.3 ± 12.8	53.4 ± 10.9
Sex			
Male	88,142 (50.4)	79,462 (50.6)	8680 (48.2)
Female	86,814 (49.6)	77,496 (49.4)	9318 (51.8)
Marital status			
Single	49,797 (28.5)	45,566 (29.0)	4231 (23.5)
Married and cohabitating	100,224 (57.3)	90,368 (57.6)	9856 (54.8)
Married and living separately	3018 (1.7)	2593 (1.7)	425 (2.4)
Divorced	17,708 (10.1)	14,894 (9.5)	2814 (15.6)
Widowed	4209 (2.4)	3537 (2.3)	672 (3.7)
Level of education			
Doctorate	8203 (4.7)	7839 (5.0)	364 (2.0)
Master's or equivalent	34,121 (19.5)	31,734 (20.2)	2387 (13.3)
Bachelor's or equivalent	55,698 (31.8)	50,403 (32.1)	5295 (29.4)
Post-secondary non-tertiary	16,210 (9.3)	14,778 (9.4)	1432 (8.0)
Secondary level 2	53,133 (30.4)	45,630 (29.1)	7503 (41.7)
Secondary level 1	2939 (1.7)	2266 (1.4)	673 (3.7)
Primary	529 (0.3)	382 (0.2)	147 (0.8)
Still in general education	8 (0.0)	5 (0.0)	3 (0.0)
Still in vocational training	4115 (2.4)	3921 (2.5)	194 (1.1)
Migration background			
No	149,386 (85.4)	134,267 (85.5)	15,119 (84.0)
Yes	25,570 (14.6)	22,691 (14.5)	2879 (16.0)
PM2.5	12.6 ± 1.7	12.6 ± 1.7	12.6 ± 1.7
NO_2	24.8 ± 8.7	24.7 ± 8.7	24.9 ± 8.7
Vegetation period NDVI	0.54 ± 0.1	0.54 ± 0.1	0.54 ± 0.1

responses 2, 3, 4, and 5) and being exposed to high road traffic noise resulted in a superadditive effect on the risk of poor SRH.

Results of our logistic regression analyses are presented as ORs with 95 % CIs, while the results of our path analysis are presented as unstandardized probit-scale coefficients with 95 % CIs. Statistical significance was defined as a two-sided p-value <0.05. Most analyses were conducted in Stata/BE 18.0 for Mac. The path analysis was conducted in R version 3.6.0 and R Studio version 2025.09.1 + 401 using the lavaan package (lavaan, 2012). All code is provided in the supplementary materials.

3. Results

After excluding participants with missing exposure or outcome data, 174,596 participants (85.2 %) remained. A STROBE flow diagram describing participant exclusion is shown in Fig. 1. Descriptive statistics for excluded participants are presented in Table S1.

Characteristics of the participants are summarized in Table 1. Among 174,956 participants included in our analysis, the mean age was 49 years, with a balanced distribution of males and females. Just over 10 % reported poor SRH. Most participants (62 %) were not at all annoyed by nighttime transportation noise, while 27 % reported slight or moderate annoyance and 10 % reported strong or extreme annoyance. More than 78 % lived in areas with road traffic noise below 55 dB(A). The participants were predominantly married and cohabitating, highly educated, and without a migration background.

A crosstabulation of nighttime transportation noise annoyance and annual mean road traffic noise is presented in Table 2. The highest proportion of participants reporting no nighttime transportation noise annoyance and the lowest proportion reporting both slight/moderate and strong/extreme nighttime transportation noise annoyance resided in geographic areas missing END noise measurements. In contrast, the lowest proportion reporting no annoyance and the highest reporting slight, moderate, strong, or extreme annoyance resided in areas with annual mean road traffic noise of 70 dB(A) and higher. A higher proportion of those living in areas with road traffic noise ≥55 dB(A) reported slight/moderate and strong/extreme annoyance than those living in areas with road traffic noise <55 dB(A).

We observed weak correlations or associations between most variables (Table S2). A chi-square test of independence for road traffic noise

Table 2
Crosstabulation of nighttime transportation noise annoyance levels and annual mean road traffic noise levels, including both the original 7-level variable and the dichotomized variable.

Nighttime transportation noise annoyance	Total	Not at all annoyed	Slightly/moderately annoyed	Strongly/extremely annoyed
No measurement	52,514 (30.0)	36,652 (69.8)	11,944 (22.7)	3918 (7.5)
<55 dB(A)	84,110 (48.1)	53,671 (63.8)	23,027 (27.38)	7412 (8.8)
55 to < 60 dB(A)	15,951 (9.1)	8532 (53.5)	5283 (33.1)	2136 (13.4)
60 to < 65 dB(A)	10,121 (5.8)	4721 (46.7)	3505 (34.6)	1895 (18.7)
65 to < 70 dB(A)	7898 (4.5)	3369 (42.7)	2751 (34.8)	1778 (22.5)
70 to < 75 dB(A)	3654 (2.1)	1467 (40.2)	1236 (33.8)	951 (26.0)
75+ dB(A)	708 (0.4)	263 (37.1)	255 (36.0)	190 (26.8)
Low noise (<55 dB(A))	136,624 (78.1)	90,323 (66.1)	34,971 (25.6)	11,330 (8.3)
High noise (≥55 dB(A))	38,332 (21.9)	18,352 (47.9)	13,030 (34.0)	6950 (18.1)

Note: Total counts and column percentages are shown for each road traffic noise exposure category. Counts and row percentages are shown for each road traffic noise exposure category across the three levels of nighttime transportation noise annoyance for the main model sample.

and nighttime transportation noise annoyance produced a test statistic of 5100 with two degrees of freedom and a p-value of <0.001, and a corresponding Cramer's V of 0.17, indicating a significant association of weak-to-moderate strength.

The results of our analysis for all included participants are presented in Table 3. In our noise-only main model, annual average exposure to high noise (≥55 dB(A)) was associated with 7 % higher odds of reporting poor health (95 % CI 1.03, 1.11), and this association was only slightly reduced by the inclusion of co-exposures in the multi-exposure main model (OR 1.06, 95 % CI 1.01; 1.10). Similarly, associations between both levels of nighttime transportation noise annoyance and poor SRH were similar across noise-only and multi-exposure main models, with slight/moderate annoyance being associated with a 28 % increase in the odds of poor SRH (95 % CI 1.23; 1.32) and strong/extreme annoyance being associated with a 73 % increase in the odds of poor SRH (95 % CI 1.65; 1.81) in the multi-exposure main model. In the multi-exposure main model with both objectively assessed noise exposure and nighttime transportation noise annoyance included, the association between high road traffic noise and poor SRH disappeared (OR 0.99, 95 % CI 0.95; 1.03), while the associations for both levels of nighttime transportation noise annoyance were unchanged.

Results stratified by NAKO study site are shown in Fig. 2 and Table S3. We observed variation in the strength and direction of associations across sites between annual mean road traffic noise ≥55 dB(A) and poor SRH. The associations ranged from OR 0.88 in Bremen (95 % CI 0.75; 1.03) to OR 1.34 in Hannover (95 % CI 1.13; 1.58). We also observed variation in the strength (but not direction) of the associations between nighttime transportation noise annoyance and SRH across study sites. The association between slight/moderate annoyance and poor SRH ranged from OR 1.13 in Halle (95 % CI 0.95; 1.33) to OR 1.47 in Augsburg (95 % CI 1.31; 1.65), while associations for strong/extreme annoyance ranged from OR 1.43 in Leipzig (95 % CI 1.21; 1.71) to OR 2.06 in Halle (95 % CI 1.68; 2.53).

The results of analyses stratified by sex are shown in Fig. 3 and Table S4. When stratifying by sex, the results were generally consistent with those from the main analysis. The associations between both annual mean road traffic noise ≥55 dB(A) and both levels of nighttime transportation noise annoyance were similar across sexes in all models. We did not find any evidence of significant interactions between sex and either noise variable (Table S5).

Table 3
Logistic regression results for three sets of models: noise-only minimum models, noise-only main models, and multi-exposure main models. ORs and 95% CIs are presented.

Model	Noise-only minimum model Odds ratios and 95% confidence intervals	Noise-only main model Odds ratios and 95% confidence intervals	Multi-exposure main model Odds ratios and 95% confidence intervals
Annual mean road traffic noise			
Low noise (<55 dB(A))	REF	REF	REF
High noise (≥55 dB(A))	1.12 (1.08; 1.17)	1.07 (1.03; 1.11)	1.06 (1.01; 1.10)
Environmental co-exposures			
$PM_{2.5}$	–	–	1.03 (1.01; 1.05)
NO_2	–	–	1.00 (0.97; 1.02)
Vegetation period NDVI	–	–	1.05 (1.03; 1.08)
Nighttime transportation noise annoyance			
Not at all annoyed	REF	REF	REF
Slightly or moderately annoyed	1.29 (1.24; 1.33)	1.28 (1.23; 1.33)	1.28 (1.23; 1.32)
Strongly or extremely annoyed	1.79 (1.71; 1.87)	1.74 (1.66; 1.82)	1.73 (1.65; 1.81)
Environmental co-exposures			
$PM_{2.5}$	–	–	1.03 (1.01; 1.05)
NO_2	–	–	0.99 (0.97; 1.02)
Vegetation period NDVI	–	–	1.03 (1.00; 1.06)
Annual mean road traffic noise			
Low noise (<55 dB(A))	REF	REF	REF
High noise (≥55 dB(A))	1.04 (1.00; 1.08)	0.99 (0.95; 1.03)	0.99 (0.95; 1.03)
Nighttime transportation noise annoyance			
Not at all annoyed	REF	REF	REF
Slightly or moderately annoyed	1.28 (1.24; 1.33)	1.28 (1.24; 1.33)	1.28 (1.23; 1.32)
Strongly or extremely annoyed	1.77 (1.69; 1.86)	1.74 (1.66; 1.83)	1.74 (1.66; 1.82)
Environmental co-exposures			
$PM_{2.5}$	–	–	1.03 (1.01; 1.05)
NO_2	–	–	0.99 (0.97; 1.02)
Vegetation period NDVI	–	–	1.03 (1.01; 1.06)

Note: Minimum model includes the following covariates: age and sex. Main model includes age, sex, marital status, level of education, migration background, and study site.

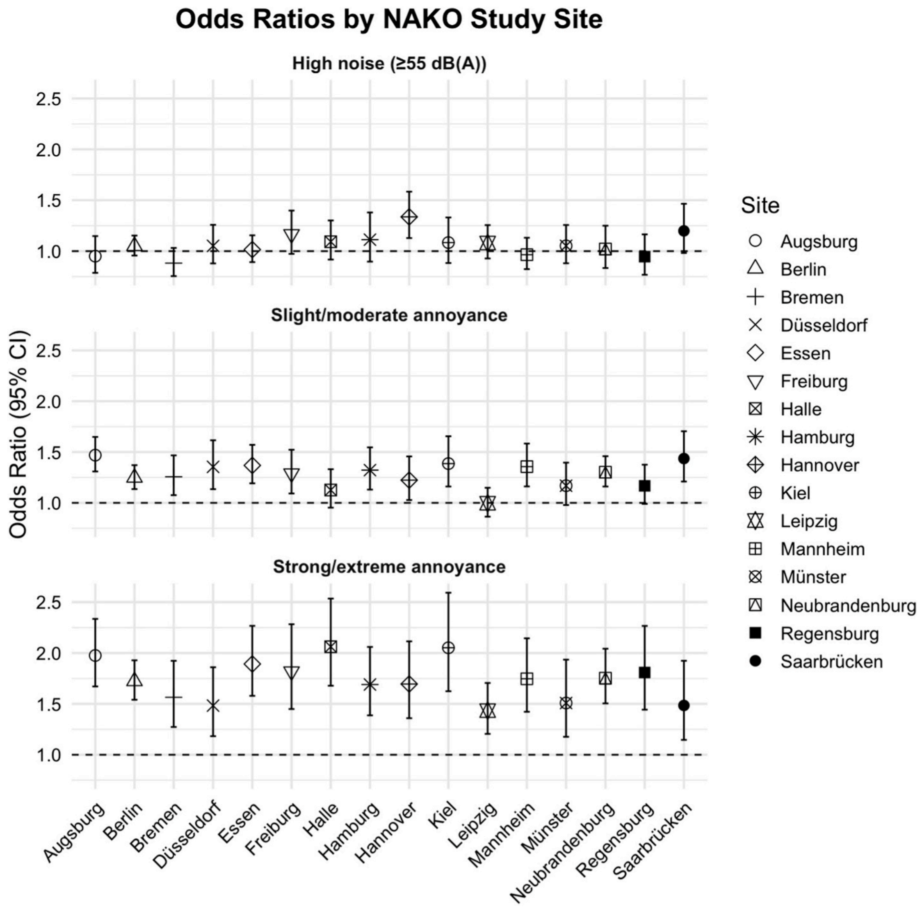

Fig. 2. Results for multi-exposure main models stratified by study site. ORs and 95 % CIs are presented.
Note: The model for road traffic noise was adjusted for all main model covariates and included all three co-exposures. The model for nighttime transportation noise annoyance was adjusted for all main model covariates and included all three co-exposures.

In the path model (Fig. 4 and Table S6), annual mean road traffic noise ≥55 dB(A) predicted a higher likelihood of nighttime transportation noise annoyance (b = 0.43, 95 % CI: 0.41; 0.44). Nighttime transportation noise annoyance, in turn, positively predicted poor SRH (b = 0.12, 95 % CI: 0.11; 0.13). The direct effect of road traffic noise on poor SRH was negative, nonsignificant, and very small in magnitude (b = −0.02, 95 % CI: 0.040; 0.002); this sign reversal reflects suppression, where annoyance carries noise's harmful association with poor SRH. Mediation analysis indicated that nighttime transportation noise annoyance mediated the association between road traffic noise and poor SRH, with a positive indirect effect (0.050, 95 % CI: 0.045; 0.054). The total effect, combining direct and indirect pathways, was positive but smaller in magnitude (0.03, 95 % CI: 0.01; 0.05), indicating that high road traffic noise increases the likelihood of poor SRH primarily through nighttime transportation noise annoyance. Model fit indices were consistent with a just-identified model (df = 0) ($\chi^2(0) = 0.00$, CFI = 1.00, TLI = 1.00, RMSEA = 0.000, SRMR = 0.000).

Full results of all sensitivity analyses are provided in Tables S7-S11. Restricting the sample to participants who had resided at their current address for at least five years (N = 128,843) did not meaningfully alter the associations for either exposure (Table S7). Results for the analysis restricted to participants residing in areas with mandated END noise measurements were identical to those of the main analysis: ≥55 dB(A) was associated with a 6 % increase in the odds of poor SRH (95 % CI, 1.01–1.10) (Table S8). Using a multi-categorical variable for annual mean traffic noise (Table S9) produced results consistent with the main analysis for most noise categories, except for the ≥65 and < 70 dB(A) group, which showed no association (OR 0.99, 95 % CI 0.92–1.08). The highest noise category (≥75 dB(A)) was associated with substantially higher odds of poor SRH (OR 1.17, 95 % CI 0.92–1.48) compared to low-noise areas. Analyses using the alternative annoyance variable (Table S9) yielded expected results: being extremely annoyed (vs. not at all or slightly annoyed) was associated with 75 % higher odds of poor SRH (95 % CI 1.64–1.86), and being moderately or strongly annoyed with 42 % higher odds (OR 1.42, 95 % CI 1.36–1.48). Multinomial logistic regression (Table S10) with a three-level SRH outcome produced expected results, showing that, in comparison to reporting very good or excellent health, those slightly or moderately annoyed had a 47 % higher odds of reporting poor SRH (95 % CI 1.42; 1.53), and those strongly or extremely annoyed had more than double the odds (OR 2.10, 95 % CI 1.99; 2.21), while annual mean traffic noise ≥55 dB(A) was associated with 7 % higher odds (95 % CI 1.03; 1.12). The odds of reporting good health (vs. very good or excellent) increased by 2 % for annual mean traffic noise ≥55 dB(A) (95 % CI 0.99; 1.05), 24 % for slight or moderate annoyance (95 % CI 1.21–1.27), and 32 % for strong or extreme annoyance (95 % CI 1.27–1.37). Our additive interaction analysis (Table S11) did not reveal any significant super- or sub-additive interaction.

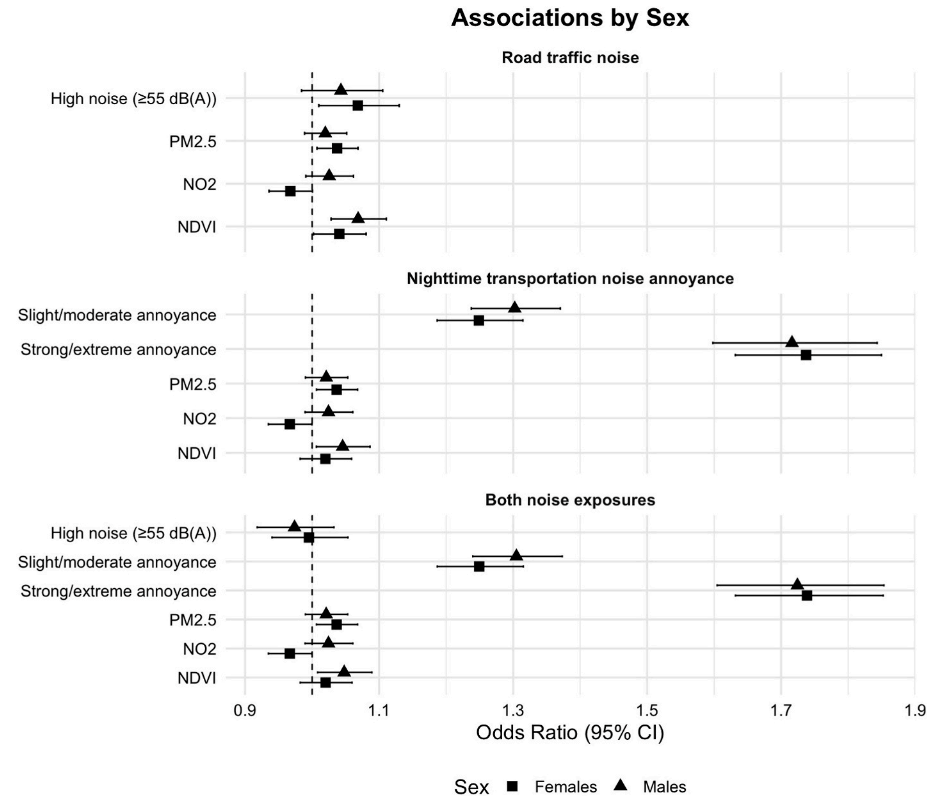

Fig. 3. Results of multi-exposure main models stratified by sex. Odds ratios and 95 % confidence intervals are shown.
Note: All models were adjusted for age, marital status, education, migration background, and study site. Estimates for males are shown as triangles, while estimates for females are shown as squares.

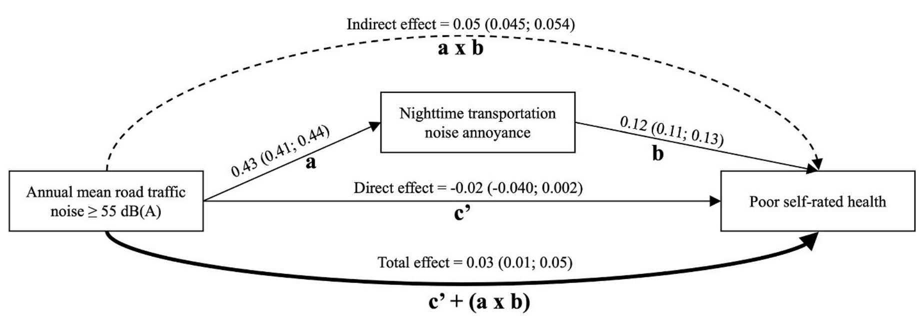

Fig. 4. Results of a path analysis to evaluate the mediating effect of nighttime transportation noise annoyance on the association between annual mean road traffic noise and poor SRH. ORs and 95 % CIs are presented.
Note: Solid thin black lines represent direct effects, the dashed line represents the indirect effect of annual mean traffic noise on poor SRH through nighttime transportation noise annoyance, and the solid thick black line represents the total effect of both exposures on poor SRH. All models included the following covariates: age, sex, marital status, education, migration background, study site, PM2.5, NO2, and vegetation period NDVI.

4. Discussion

We found that annual mean road traffic noise at or above the END recommended threshold of annual mean Lden of 55 dB(A) was associated with six percent higher odds of poor SRH, even when adjusting for three key health-related co-occurring exposures ($PM_{2.5}$, NO_2, and NDVI). This finding aligns with some previous studies, but not with others. Four studies of road traffic noise and SRH conducted in Bulgaria (Dzhambov et al., 2023), Germany (Riedel et al., 2015), the Netherlands (Klompmaker et al., 2019), and the United Kingdom (Mutz et al., 2021) did not find any significant association, while one study in Switzerland found a weak relationship (Brink, 2011), and another in Finland found an association only in men (Halonen et al., 2014). We found that subjectively reported slight or moderate nighttime transportation noise annoyance was associated with 28 % higher odds of poor SRH, and strong or extreme annoyance with 73 % higher odds. Four previous studies have found an association between subjectively reported road, rail, and/or air traffic noise annoyance and worse SRH in Cameroon (Totouom et al., 2023), France (Kodji et al., 2023), and Germany (Riedel et al., 2015, 2017), while two in France (Kodji et al., 2024) and the Netherlands (Putrik et al., 2015) did not, and another study in France reported an association only among men (Baudin et al., 2021). In a model that included both noise variables, we found that only nighttime transportation noise annoyance remained associated with SRH. In the only other known study combining both objectively measured road traffic noise and subjective transportation noise annoyance measures, researchers in Germany also found that annoyance was more strongly associated with poor SRH (Riedel et al., 2015). Though not directly related, as they did not include objective measurements of road traffic noise, findings from studies on objectively measured air traffic noise and air traffic noise annoyance in France also found that air traffic noise annoyance was more strongly associated with SRH than the corresponding objective measurement (Baudin et al., 2021; Kodji et al., 2023).

We did not find meaningful differences between males and females, unlike two previous studies. One study of nearly 16,000 adults in Finland found that only men had significantly higher odds of poor SRH when exposed to annual-average road traffic noise >60 dB(A) Lden (compared to ≤ 45) (Halonen et al., 2014). They could not explain this, noting that previous studies had found that women are more likely to report traffic noise annoyance and related sleep disturbances. Another study of just over 1200 adults in France found that subjectively reported air traffic noise annoyance was only significantly associated with higher odds of poor SRH among men, which they interpreted as being related to physiological differences in the response to noise, which may be more likely to lead to hypertension among men (Baudin et al., 2021). In contrast, we found that increases in the odds of poor SRH in response to road traffic noise and nighttime transportation noise annoyance were similar across sexes. These differences between previous studies and ours could be due to the larger sample size in our study or to differences in the study populations.

We found that road traffic noise exposure was not directly associated with SRH and increased the odds of poor SRH only indirectly through its association with nighttime transportation noise annoyance. Similar findings have been reported in studies of air traffic noise; for example, a longitudinal study in France found that nearly all of the association between aircraft noise and SRH was mediated by noise annoyance (Kodji et al., 2024). Other studies have highlighted the central role of annoyance in explaining the health impacts of environmental noise, particularly for subjective health outcomes, but have not formally tested mediation using advanced modeling approaches such as path analysis or structural equation modeling (Halonen et al., 2014; Riedel et al., 2015).

Our findings might seem to suggest that road traffic noise exposure is not detrimental to health in the absence of corresponding annoyance. However, one of the main limitations of our study is that END noise mapping data are subject to several methodological and practical constraints (Staab et al., 2025). These include inconsistent definitions of urban areas, variability in input data and modeling methods across regions, and incomplete coverage of secondary roads and suburban areas, all of which can lead to underestimation of true noise exposure. Additionally, the spatial resolution and post-processing of END data can introduce geometric artifacts and data quality issues, potentially affecting the accuracy of exposure assessment (Staab et al., 2025). Beyond the specific limitations of END noise mapping, area-level noise averages themselves are also prone to underestimating individual exposure. Such averages fail to account for the position of a dwelling or bedroom within a residential building, whether or not the dwelling or bedroom faces a street, and the adequacy of soundproofing. This may lead to biased estimates, wherein the magnitude of the direct health effects caused by road traffic noise is underestimated (Vienneau et al., 2019). Area-level estimates were also specific to the participants' place of residence and did not capture possible exposure elsewhere, such as in the workplace or while commuting. This lack of precision in the exposure assessment could also be exacerbated by socioeconomic characteristics, wherein those with more resources are better able to avoid noise at home by living in buildings with higher-quality soundproofing, living in quieter places within the city, and traveling more frequently to quiet places away from home. Furthermore, we were unable to include objective measurements of rail or air traffic noise, preventing the generalizability of our findings to all types of transportation noise. Objective measurements were also only available for the year 2017, leading to possible exposure misclassification due to this temporal mismatch. Taken together, all of these limitations suggest that our estimates of the direct estimated effects of road traffic noise exposure on SRH may be conservative or biased, and highlight the need for further research using higher-resolution and more comprehensive noise modeling.

Our study also has other limitations. Due to the cross-sectional design of the study, it is not possible to determine whether road traffic noise exposure or nighttime transportation noise annoyance have any causal effect on SRH, nor is it possible to ascertain the directionality of the association between nighttime transportation noise annoyance and SRH. It is possible that people who experience high stress levels, who are unhealthy, or who consider themselves to be unhealthy may be more likely to be annoyed by noise, or that those who are more sensitive to or annoyed by noise may also be more likely to categorize their health as fair or poor. However, our descriptive analysis revealed a dose-response pattern between increasing dB(A) Lden and increasingly higher proportions of participants reporting annoyance, and our SEM showed a strong association between objectively measured road traffic noise and nighttime transportation noise annoyance, suggesting that the possibility of bias due to differences in noise sensitivity may be somewhat limited.

We did not use the International Commission on the Biological Effects of Noise/International Organization for Standardization (ICBEN/ISO) wording for the question for assessing noise annoyance, limiting comparability with other research. However, most studies regarding traffic noise annoyance in Germany use questions that also deviate from the ICBEN/ISO standard (Wolf et al., 2020). We were also unable to distinguish between single sources of transportation noise annoyance, as the question asked about annoyance from three types of transportation noise simultaneously. We also could not consider noise sensitivity as a covariate or as a mediating or moderating factor due to a lack of data. Additionally, the hypothetical nature of the question on nighttime transportation noise annoyance and the dependence of the response on whether the bedroom window is open have also introduced some possible bias. We did not have information on participants' actual nighttime window-opening behavior, bedroom window type, or soundproofing. As a result, some participants who reported annoyance may not actually experience it if they keep their windows closed at night, while others who do open their windows may be more likely to report higher annoyance. This limitation could lead to exposure misclassification, as responses may reflect not only situational annoyance but also an individual's general noise sensitivity. However, as mentioned previously, we did observe a positive relationship between increasing road traffic noise and increasing nighttime transportation noise annoyance, suggesting that this possible bias may be limited.

Finally, it is possible that these results are biased by residual confounding by unmeasured variables or due to a lack of precision in the measurement of included confounders. For example, our sex variable did not capture any aspect of sexual diversity in Germany, as it only became possible for intersex people to register themselves as “diverse” rather than male or female in local civil registries starting in 2018 (when the NAKO's baseline data collection was nearly complete). Additionally, we were unable to include any aspect of gender identity in our analyses due to a lack of data, potentially contributing to exposure misclassification for objectively measured road traffic noise due to differences in exposure patterns based on gendered roles and practices (Bolte et al., 2021).

Our study has some important strengths. NAKO's strategies for recruitment, data collection, data management, and data quality assurance were designed and implemented by a consortium of 27 German scientific institutions and with input from experts from many disciplines, making it a reliable data source (Peters et al., 2022; Rach et al., 2025; Staab et al., 2025). It is the largest known study of the association between transportation noise annoyance and SRH, and one of the largest of objectively measured traffic noise and health, with a sample size of nearly 175,000 adults across 16 regions of Germany.

Future research should make use of NAKO's longitudinal data to assess the impact of transportation noise exposure and related annoyance on SRH over time. Subsequent studies should also incorporate an assessment of sleep disturbance related to traffic noise to generate evidence on how nighttime transportation noise, sleep quality, and health are interrelated. An exploration of how personality traits, noise sensitivity, stress, and mental health may mediate the relationship between noise and SRH would also be of interest. Future studies could also aim to understand the dynamics and directionality between transportation noise annoyance and SRH by incorporating an assessment of objectively measured health symptoms. Research that makes use of more precise objective noise measurements would facilitate a more reliable characterization of the direct effect of noise exposure on SRH. It is also important to note that nearly all previous known studies, and our study, have been implemented in Europe. In fact, only three studies have been implemented outside of Western Europe: one in Bulgaria (Dzhambov et al., 2023), one in Finland (Halonen et al., 2014), and one in Cameroon (Totouom et al., 2023). More research is needed outside of the Western European region.

Despite the limitations of our study and the need for additional research, our findings align with existing evidence linking transportation noise exposure to a range of objectively measured and subjectively reported health outcomes (Welch et al., 2023). Policymakers in Germany have become more aware of the health risks associated with transportation noise in recent years and have begun implementing comprehensive, strategic interventions to reduce noise exposure. For example, Berlin recently updated its Noise Action Plan ("Lärmaktionsplan") for 2024–2029 (Berlin Senate Department for the Environment and Mobility, 2025), which included a variety of policies and interventions such as road surface renewal, the implementation of lower speed limits at night, window soundproofing, and the expansion of designated quiet recreational spaces. Beyond reducing exposure to transportation noise itself, local policymakers can reduce transportation noise annoyance through transparent, active, and bidirectional communication with the public, as well as engaging citizens in the development of interventions, as these efforts can help to increase trust, reduce uncertainty, and increase perceived environmental control among community members (Riedel et al., 2021). Efforts should continue to raise policymakers' awareness across Europe and in other regions of the health risks posed by transportation noise and transportation noise annoyance, as well as the policy options available to address them.

5. Conclusions

These results add to a growing body of evidence highlighting the health risks of transportation noise exposure and related annoyance. Decision-makers should consider both policies to reduce transportation noise as well as community-level interventions to mitigate transportation noise annoyance and its health consequences. Given the methodological limitations of END noise mapping data and area-level exposure estimates, future research should prioritize higher-resolution, individualized noise assessments and longitudinal designs to clarify causal pathways. Expanding research beyond Western Europe and incorporating objective health markers, sleep disturbance, stress, and noise sensitivity would further advance scientific understanding of how transportation noise affects population health and well-being.

Declaration of generative AI and AI-assisted technologies in the writing process:

During the preparation of this work the authors used Perplexity AI (https://www.perplexity.ai) in order to improve the clarity, precision, and succinctness of the manuscript text; to ensure that all journal formatting requirements were met; and to search for relevant references. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

S. Claire Slesinski: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Gabriele Bolte:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Sida Zhuang:** Writing – review & editing, Methodology. **Tobia Lakes:** Writing – review & editing, Methodology. **Eva Rehfuess:** Writing – review & editing, Methodology, Conceptualization. **Jeroen Staab:** Writing – review & editing, Data curation. **Fabian Bamberg:** Writing – review & editing. **Hansjörg Baurecht:** Writing – review & editing. **Heiko Becher:** Writing – review & editing. **Hermann Brenner:** Writing – review & editing. **Nadine Glaser:** Writing – review & editing. **Karin Halina Greiser:** Writing – review & editing. **Kathrin Günther:** Writing – review & editing. **Volker Harth:** Writing – review & editing. **Jana-Kristin Heise:** Writing – review & editing. **Thomas Keil:** Writing – review & editing. **Carolina J. Klett-Tammen:** Writing – review & editing. **Michael Leitzmann:** Writing – review & editing. **Wolfgang Lieb:** Writing – review & editing. **Claudia Meinke-Franze:** Writing – review & editing. **Rafael Mikolajczyk:** Writing – review & editing. **Ilais Moreno Velásquez:** Writing – review & editing. **Ulrich Mueller:** Writing – review & editing. **Rajini Nagrani:** Writing – review & editing. **Nadia Obi:** Writing – review & editing. **Cara Övermöhle:** Writing – review & editing. **Tobias Pischon:** Writing – review & editing. **Tamara Schikowski:** Writing – review & editing. **Sabine Schipf:** Writing – review & editing. **Christopher L. Schlett:** Writing – review & editing. **Börge Schmidt:** Writing – review & editing. **Matthias B. Schulze:** Writing – review & editing. **Thaddäus Tönnies:** Writing – review & editing. **Stefan N. Willich:** Writing – review & editing. **Annette Peters:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Alexandra Schneider:** Writing – review & editing, Supervision, Resources, Methodology, Data curation, Conceptualization. **Kathrin Wolf:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Ethics approval and consent to participate

The German National Cohort (NAKO) study is performed with the approval of the relevant ethics committees and is in accordance with national law and with the Declaration of Helsinki of 1975 (in the current, revised version). Written informed consent was obtained from all individual participants included in the study.

Availability of data and materials

Access to and use of NAKO data and biosamples can be obtained via an electronic application portal (https://transfer.nako.de).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced or appeared to influence the work reported in this paper.

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List of abbreviations

CI: Confidence interval
DAG: Directed Acyclic Graph
dB(A): Decibels adjusted to human hearing
EEA: European Environment Agency
EIONET: European Environment Information and Observation Network
END: European Noise Directive
ICBEN/ISO: International Commission on the Biological Effects of Noise International Organization for Standardization
Lden: Day-evening-night level
NAKO: German National Cohort
OR: Odds ratio
Europe PMC: Europe PubMed Central
SRH: Self-rated health
UNESCO: United Nations Education, Scientific, and Cultural Organization

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2026.123885.

Data availability

Data will be made available on request.

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