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Indoor and outdoor road traffic noise and incident diabetes mellitus: Results from a longitudinal German cohort study

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Background: Road traffic noise affects a large number of people in urbanized areas. Recent epidemiological evidence indicates that environmental noise exposure may not only be associated with cardiovascular but also with cardio-metabolic outcomes. This prospective cohort study investigated the effect of outdoor and indoor residential road traffic noise on incident type 2 diabetes mellitus (T2DM).
Methods: We used data from 3,396 participants of age 45–75 years of the Heinz Nixdorf Recall study being non-diabetic at baseline (2000–2003). T2DM was defined via blood glucose level, incident intake of an anti-diabetic drug during follow-up or self-reported physician diagnosis at follow-up examination (2005–2008). Weighted 24-h (L_{den}) and night-time (L_{night}) mean road traffic noise was assessed according to the European Union directive 2002/49/EC. Road traffic noise exposure indoors was modeled taking into account the participants' room orientation, ventilation behavior and window insulation (n = 2,697). We applied Poisson regression analyses to estimate relative risks (RRs) of incident T2DM, adjusting for demographic characteristics, lifestyle factors, and air pollution exposure (NO_2 or $PM_{2.5}$).
Results: A 10-dB(A) increase in outdoor road traffic noise (L_{den}) was associated with an RR of 1.09 (95% confidence interval, 0.96–1.24) for T2DM in the fully adjusted model. Models including $PM_{2.5}$ or NO_2 yielded RRs of 1.09 (0.96–1.24) and 1.11 (0.97–1.27), respectively. In analyses with road traffic noise (L_{den}) exposure indoors, we observed similar RRs with smaller confidence intervals (1.11 [1.01–1.21]).
Conclusions: Our analyses suggest that long-term exposure to indoor and outdoor road traffic noise may increase the risk of developing T2DM, independent of air pollution exposure.

Introduction

Noise is a growing environmental health problem causing at least 10,000 premature deaths in Europe annually.[1] Surpassing railway, aircraft, and industry, road traffic represents the most ubiquitous source of noise in Europe both inside and outside urban areas: In 2012, about 100 million Europeans were affected by road-traffic noise exceeding the recommended day, evening, and night noise levels of 55 decibels (dB(A)).[2] In the last few decades, evidence supporting a harmful association between noise exposure and various aspects of cardiovascular health has accumulated.[3] Recently, first epidemiologic studies investigated associations between noise and metabolic outcomes, observing positive associations between road traffic noise and type 2 diabetes mellitus (T2DM).[4–7] Potential biological pathways of traffic noise–related health effects include noise-induced stress, activating the autonomic nervous system/hypothalamus–pituitary–adrenal (HPA) axis both directly and through the personal perception of noise as a stressor, the so-called noise annoyance. A second pathway links exposure to ambient night noise to sleep disturbances, which may also lead to altered metabolic functions.[8,9] Epidemiologic studies support this theory, showing that both short-term and long-term exposure to environmental traffic noise was associated with an increase in body mass index (BMI) and/or waist circumference (WC).[10–13] Imprecise exposure assessment to road traffic noise may originate from noise-abating factors of the outer shell of the residence. The three studies that previously investigated indoor noise exposure differed from our study in that they evaluated other endpoints (e.g., blood pressure[14] and markers of obesity[13] or used only the bedroom orientation as a surrogate marker for indoor noise exposure.[5,13] The use of indoor noise levels has the advantage of less exposure misclassification and less correlation with air pollution (AP) levels and thus reduced potential confounding

What this study adds

- Our study adds to prior evidence that traffic noise is associated with cardio-metabolic disease.
- Estimates for noise exposure were robust to air pollution adjustment, indicating independence of associations.
- Using modeled indoor noise by including information on window orientation and insulation can improve estimation of traffic noise exposure.

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Availability of Data and Code: Data of the Heinz Nixdorf Recall (HNR) cohort can be provided upon agreement of the Institute of Medical Informatics, Biometry and Epidemiology in Essen by the corresponding author. The code for reproduction of the analyses can be obtained through contacting the corresponding author.

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by AP. As AP and traffic noise exposure share traffic as a common source, considering only one of the two exposures in an analysis may lead to confounded associations.[15] This is of particular relevance when researching cardio-metabolic outcomes, as current evidence suggests a possible positive association between AP and T2DM.[16–18] The aim of this study was to investigate the association between long-term residential exposure to road traffic noise and incident T2DM during a mean follow-up period of 5 years, using several measures of noise exposure outside and inside the residence within the German population-based Heinz Nixdorf Recall (HNR) cohort.

Materials and methods

Study population

We used data from the population-based longitudinal HNR (Risk factors, evaluation of coronary calcium and lifestyle) cohort study located in three adjacent cities (Bochum, Essen, and Mülheim/Ruhr) within the highly urbanized German Ruhr Area. Information on the study design has been described elsewhere.[19,20] In short, 4,814 participants (45–75 years of age), randomly selected (age-stratified) from municipal population registries, were recruited at baseline (response rate 56.0%) between December 2000 and August 2003 (Figure 2). About 5 years later (2006–2008), the first follow-up examination was performed including 4,157 participants (response rate of eligible participants 90.2%). Assessments included self-administered questionnaires, face-to-face interviews, clinical examinations, and comprehensive laboratory analyses. The HNR study was approved by the ethics committee of the University Hospital Essen. All participants gave their written informed consent.

Noise assessment

Outdoor road traffic noise was modeled according to the 2002/49/EC Directive.[21] Noise modeling was performed on behalf of the local city administrations who supplied source-specific traffic noise values applying the VBUS/RLS-90[22] method and using the software CadnA.[23] For the year 2006, averaged day–evening–night (24-hour) noise levels (L_{den}) and averaged levels of nighttime noise (L_{night}, 22:00–06:00 hour) were modeled considering the following factors: small-scale topography of the area, building dimensions, noise barriers, street axis, type-specific vehicle traffic density, speed limit, and type of road surface.[22] The indicator L_{den} is a weighted noise value integrating 12 hours for day (6:00–18:00), 6 hours for evening (18:00–22:00), and 8 hours for nighttime (22:00–6:00). L_{den} considers increased annoyance reactions toward traffic noise during evening and night hours, by adding a penalty of 5 dB to evening noise levels and a penalty of 10 dB to night noise levels. The immission of noise at the participant's residence was estimated at a height of 4 ± 0.2 m selecting the highest estimated noise level within a buffer of 10 m from the residence. In the HNR study, we used noise values estimated at the residential addresses of study participants at baseline (2000–2003), applying the geographic information system ArcGIS. We thereby assumed that average noise levels were relatively stable over time in terms of spatial distribution and exposure level.

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Indoor noise from outside sources (i.e., traffic) was estimated for 2,697 study participants through combining outdoor noise values (L_{den} and L_{night}) with individual apartment information, which was collected in the 3- to 4-year follow-up questionnaire. Indoor noise values for the living room (Indoor L_{den}) and the bedroom (Indoor L_{night}) were derived from outdoor noise estimates through information on room and window orientation, window opening/closing habits, and window type[14] (Figure 1). If the room was facing a street other than the postal address street or a side street, 20 dB(A) were subtracted from the outdoor noise level, according to a model for traffic noise in cities.[24] Otherwise, room-specific outdoor noise estimates were assumed

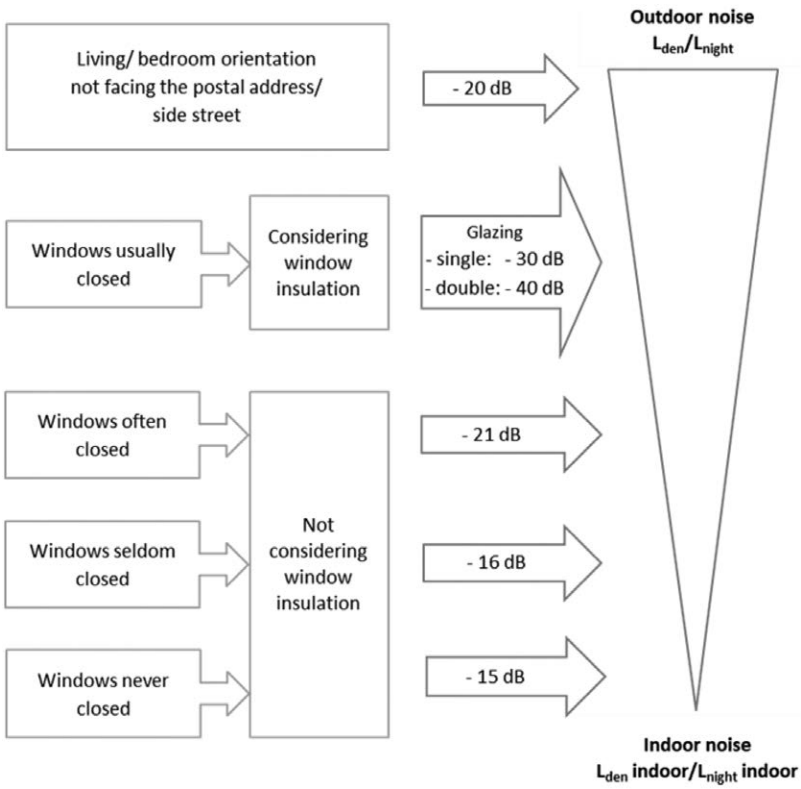

Figure 1. Indoor noise model.

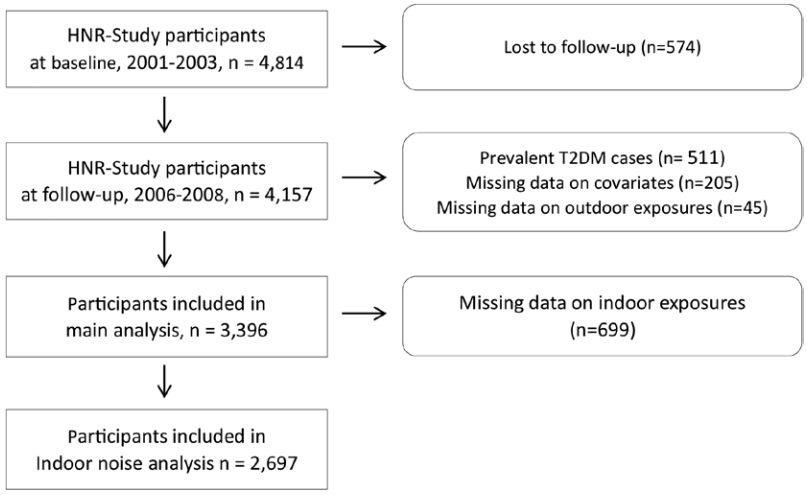

Figure 2. Flowchart of the study population.

to be similar to the noise estimates at the participants' postal address. In addition, participants were asked about their seasonal ventilation behavior. Two separate noise values were then calculated considering days with average temperatures above 10°C, which is the approximate mean temperature in the study area, as warm season (265 days) and days with average temperatures below 10°C (100 days) as cold season. If the windows were usually closed, we subtracted 30 dB(A) from the estimated room-specific outdoor noise level for single- or double-glazed windows and 40 dB(A) for sound-proof windows, according to the Good Practice Guide on Noise Exposure and Potential Health Effects (EEA 2010). "Often" (75% of the time), "seldom" (25% of the time) or "never" closed windows were taken into account by subtracting 21, 16, and 15 dB, respectively, from the room-specific noise estimates, without considering the window type. Any negative indoor noise estimates were set to zero.

Air pollution assessment

AP exposure levels for fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) were assessed by a land use regression model (LUR). The LUR model was established according to the European Study of Cohorts for Air Pollution Effects (ESCAPE) standardized procedure (ESCAPE-LUR) to estimate point-specific long-term outdoor AP.[20,25] The models performed well with R^2 of 0.88 and 0.89 for $PM_{2.5}$ and NO_2, respectively. For details, see Supplement; http://links.lww.com/EE/A29.

Assessment of type 2 diabetes mellitus

Blood glucose was assessed by glucose measurements at baseline and follow-up examinations in the University Hospital of Essen according to standardized procedures. Incident T2DM at follow-up was identified if one of the three criteria were met: (1) random blood glucose ≥200 mg/dL or fasting blood glucose ≥126 mg/dL, (2) intake of an anti-diabetic drug (ATC code A10) during follow-up, or (3) self-reported physician diagnosis after baseline assessed at follow-up examination[18] in those free of diabetes mellitus at baseline. Baseline T2DM cases were identified applying the same criteria. As study participants were aged over 45 years at baseline examinations, we assume most incident diabetes diagnoses likely to be T2DM.

Covariates

Socioeconomic, demographic and behavioral characteristics of the study population were assessed at baseline via standardized interviews and self-administered questionnaires. Height, weight, and WC were obtained from standardized anthropogenic measurements performed during the clinical examination. BMI was calculated as weight in kilograms per square meter. The individual socioeconomic status (SES) was defined as years of education according to the International Standard Classification of Education 1997[26] and was categorized into four groups (≤10, 11–13, 14–17, and ≥18 years). In addition, neighborhood SES was assessed as the unemployment rate of the neighborhood for each residential neighborhood according to administrative bounds (median size: 11,263 inhabitants). Smoking status was categorized as current smoker (during the past year), former smoker, and never smoker. Lifetime cumulative smoking exposure was assessed in pack-years. Self-reported exposure to secondhand smoke (SHS) at home, at the work place, or in other places was combined into one variable. Nutrition was assessed using a food frequency questionnaire and included in this analysis as a 26-point score (categorized in quantiles as <10, 10–12, 13–14, 15–23), with low scores characterizing a poor diet and high scores characterizing high-quality diet.[27,28] Alcohol consumption was considered as regular consumption of alcoholic drinks per week, classified as <3, 3–6, 7–20, and >20 drinks. Physical activity was assessed as binary outcome variable representing at least 30 minutes physical activity per week as well as continuous variable of weekly hours of metabolically relevant exercise. High depressive symptoms during the previous week were assessed using the 15-item short-form questionnaire of the Center for Epidemiologic Studies Depression Scale (CES-D) and included as binary variable (score of <17 versus ≥17).[29,30] Employment status was categorized as employed, pensioner, or unemployed/inactive/housewife. Annoyance due to road traffic noise during the day and at night was assessed via questionnaire in five categories. Hypertension was defined as systolic blood pressure ≥140 mm Hg or diastolic blood pressure ≥90 mm Hg or intake of blood pressure–lowering medication.

Statistical methods

We compared participants being less exposed to median noise levels (<52.25 dB) versus participants exposed to noise levels equal or above median (52.25 dB). Furthermore, we compared participants excluded due to missing data on covariates and/or exposures (n = 250) to the main study population (3,396), investigating differences in the baseline characteristics. Due to missing information on indoor noise exposure in a part of the study population, a reduced analysis sample (n = 2,697) was used for analysis of indoor noise and incident T2DM. Spearman correlation coefficients were calculated between estimated levels of

noise and AP. We used Poisson regression adapted to binary outcomes to estimate the relative risks (RRs) and 95% confidence intervals (95% CIs) for incident T2DM per 10 dB(A) increase for each noise exposure.[31] Noise exposures were included as continuous variables. For the analysis of the association of noise with T2DM, we used threshold models 45 dB for L_{den} and 35 dB for L_{night}, based on previous findings on potential health effects.[32,33] Threshold values for indoor noise originating from outdoor traffic (20 dB [L_{den}] and 10 dB [L_{night}]) were selected according to the distribution of the outdoor noise thresholds (approximately 16% of the values were below the threshold). All noise values lower than the defined threshold values were equated to the threshold value. According to current epidemiologic and clinical evidence, we identified potential confounders for inclusion in our models following the construction of a directed acyclic graph (eFigure S1; http://links.lww.com/EE/A29). Single-pollutant models were built with increasing covariate adjustment. Model 1 included age, sex, individual, and neighborhood SES; the fully adjusted model 2 was additionally adjusted for smoking status, pack-years, SHS, any regular physical activity, weekly physical activity, alcohol consumption, and nutrition index. Multipollutant models additionally included $PM_{2.5}$ or NO_2. In separate models, we included WC, BMI, and depressive symptoms as possible mediators. Linearity assumptions for continuous noise variables and covariates were evaluated using polynomials and comparing the models via Wald tests. For WC, nonlinearity was present (P = 0.03 compared to the nonfitted), and we therefore added a squared term to the model.

Effect modification

Multiplicative interaction terms were constructed to investigate possible effect modification of noise exposure by age (<65 and ≥65 years), sex (male/female), hypertension (yes/no), smoking status (never/former/current), SHS (no/yes), annoyance (not at all or slightly versus moderately or very or extremely annoyed), distance to a major road (>150/<150 m), and educational level (≤13 years/≥14 years).

Sensitivity analyses

We performed sensitivity analyses for the main models excluding participants who changed their residential addresses between baseline and follow-up examination to minimize exposure misclassification. Since evidence on possible noise thresholds for metabolic diseases is scarce, we further performed sensitivity analyses using different outdoor noise threshold values (55 dB for L_{den} and 45 dB for L_{night}). Additionally, we analyzed noise exposures as categorical variables using quantiles (<46.7, 46.7–52.3, 52.3–61.1, >61.1 dB). Analyses were performed with R version 2.13.1 (R Core Team 2013) software.

Results

We included 3,396 participants free of diabetes mellitus at baseline (Figure 1), of whom 305 (9.0 %) developed T2DM over a mean follow-up time of 5.1 years, with 162 participants self-reporting onset of T2DM or receiving antidiabetic medication and 211 participants having elevated blood glucose levels. The participants had a mean age of 58.8 years (SD 7.6; Table 1). According to the definition of the World Health Organization (based on BMI), 22.4% of the participants were obese and 47.2% overweight.[34] 5.3% and 2.5% of our participants were very or extremely annoyed by traffic noise at daytime and nighttime, respectively. Highly exposed participants reported more unfavorable health behaviors or conditions with, for example fewer education years, higher actual or former smoking rates, and less physical activity. The main study population differs in several ways from participants excluded due to missings on covariates or exposure data (n = 250). Excluded participants tended to be older, to be less educated, to have a higher WC, to be less physically active, to have worse dietary habits, and tended to live in a neighborhood with a higher unemployment rate (eTable S1; http://links.lww.com/EE/A29). Mean noise exposure values at the baseline home address were 53.9 dB for the weighted 24-hour average and 45.1 dB at night (Table 2; eFigure S2; http://links.lww.com/EE/A29). Indoor noise levels were on average 20 dB lower than the outdoor values (means for L_{den} and L_{night} indoor: 35.0 and 27.2, respectively) analyses. eTable S2; http://links.lww.com/EE/A29 showed moderate correlations between indoor and outdoor noise (0.43–0.50). AP exposures were moderately correlated with outdoor noise exposures (0.30–0.37) and weakly correlated with indoor noise levels (0.15–0.22).

Table 1

Baseline characteristics of the study population (n = 3,396), stratified by median noise exposure.

Characteristics	L_{den} < 52.25 (n = 1,698)	L_{den} ≥ 52.25 (n = 1,698)	*P* value[a]
Age (years), mean ± SD	58.8 ± 7.6	58.8 + 7.6	0.96
Sex (male), N (%)	810 (47.7)	808 (47.6)	0.97
Employment status, N (%)[b]			
Employed	756 (44.5)	753 (44.4)	0.34
Inactive/housewife/pensioner/unemployed	941 (55.5)	944 (55.6)	
Education, N (%)			
≤10 years	141 (8.3)	158 (9.3)	<0.01
11–13 years	917 (54.0)	995 (58.6)	
14–17 years	399 (23.5)	369 (21.7)	
≥18 years	241 (14.2)	176 (10.4)	
Unemployment rate in neighborhood (%), mean ± SD	11.8 ± 3.3	12.9 ± 3.4	<0.001
BMI (kg/m^2), mean ± SD	27.4 ± 4.2	27.4 ± 4.4	0.62
BMI, N (%)			
<25	505 (29.7)	525 (30.9)	0.27
25–30	825 (48.6)	779 (45.9)	
>30	368 (21.7)	394 (23.2)	
Waist circumference men (cm), mean ± SD	99.1 + 10.0	98.82 + 10.3	0.11
Waist circumference women (cm), mean ± SD	86.5 + 11.5	87.1 + 12.3	0.13
Weekly physical activity, N (%)	1,022 (60.2)	955 (56.2)	<0.05
Metabolic effective activity/week (hours), mean ± SD	12.1 + 22.0	11.5 + 24.79	0.46
Nutrition score, mean ± SD	12.7 + 3.0	12.6 + 3.2	0.71
Drinks/week, mean ± SD	5.8 + 10.1	5.5 + 9.9	0.48
Smoking status, N (%)			
Never smoker	759 (44.7)	723 (42.6)	<0.05
Former smoker	593 (34.9)	568 (33.5)	
Current smoker	346 (20.4)	407 (24.0)	
Pack-years of current/former smokers, mean ± SD	30.1 + 21.2	31.5 + 24.7	0.14
Exposure to second-hand smoke	561 (33)	655 (38.6)	<0.01
Daytime annoyance, N (%)[c]			
Not at all annoyed	997 (66.7)	583 (37.8)	<0.001
Slightly/moderately annoyed	474 (31.7)	822 (53.3)	
Very/extremely annoyed	23 (1.5)	137 (8.9)	
Nighttime annoyance, N (%)[d]			
Not at all annoyed	1,241 (83.0)	961 (62.6)	<0.001
Slightly/moderately annoyed	245 (16.4)	507 (33.1)	
Very/extremely annoyed	10 (0.7)	66 (4.3)	

[a]*P* values were derived from (a) Student's *t* tests for continuous variables and (b) Wilcoxon signed-rank tests for categorial variables.

[b]Two missings.

[c]Two hundred four of 196 missings for those exposed to L_{den} < 52.25 and ≥52.25, respectively.

[d]Two hundred two of 164 missings for those exposed to L_{den} < 52.25 and ≥52.25, respectively.

Associations between noise and T2DM

Our regression analyses showed overall weak positive but non-significant associations between outdoor road traffic noise and T2DM incidence in all models (Table 3). For example, a 10 dB

Table 2

Description of noise and air pollution exposures (2008–2009 annual means) assigned to the home address of study participants at baseline (n = 3,396)

Exposures	Min	Q1	Median	Q3	Max	Mean ± SD	IQR
L_{den} (dB)	25.9	46.7	52.3	61.1	84.6	53.9 ± 9.4	14.4
L_{night} (dB)	16.8	38.2	43.6	52.0	76.3	45.1 ± 9.1	13.8
L_{den}, indoors[a] (dB)	0.0	24.0	34.8	45.6	78.1	35.0 ± 15.3	21.6
L_{night}, indoors[a] (dB)	0.0	15.4	27.2	39.3	67.0	27.2 ± 15.7	23.9
$PM_{2.5}$ (μg/m³)	16.1	17.6	18.3	19.1	21.5	18.4 ± 1.1	1.5
NO_2 (μg/m³)	19.8	26.8	29.5	33.0	62.4	30.2 ± 4.9	6.2

[a]Indoor noise values refer to the participants with information on apartment characteristics and ventilation behavior (n = 2,697). 0 values originate from the indoor estimation method. In the regression models, 20 dB and 10 dB were chosen as lowest cutpoints for minimum indoor L_{den} and indoor L_{night} levels, respectively.
NO_2, nitrogen dioxide; $PM_{2.5}$, fine particulate matter.

Table 3

Relative risks and 95% confidence intervals for T2DM per 10 dB increase of outdoor noise exposure in the Heinz-Nixdorf-Recall Study Population (n = 3,396)

	L_{den}	L_{night}
Crude	1.12 (0.99–1.26)	1.12 (0.99–1.27)
M1[a]	1.09 (0.96–1.24)	1.09 (0.96–1.24)
M2[b]	1.09 (0.96–1.24)	1.09 (0.96–1.23)
Multipollutant analyses		
M2 + $PM_{2.5}$	1.09 (0.96–1.24)	1.09 (0.96–1.24)
M2 + NO_2	1.11 (0.97–1.27)	1.11 (0.97–1.27)
Mediation analyses		
M2 + WC	1.07 (0.95–1.21)	1.07 (0.95–1.21)
M2 + BMI	1.08 (0.96–1.23)	1.08 (0.96–1.23)
M2 + depressive symptoms	1.09 (0.96–1.24)	1.09 (0.96–1.24)

[a]Adjusted for age and sex.
[b]Additionally adjusted for education and neighborhood unemployment rate.
[c]Additionally adjusted for nutrition, alcohol consumption, smoking status, pack-years, SHS, physical activity (yes/no), weekly metabolic physical activity.
NO_2, nitrogen dioxide; $PM_{2.5}$, fine particulate matter.

increase in L_{den} resulted in an RR of 1.09 (0.96–1.24) in the fully adjusted model (M2). Multipollutant models including $PM_{2.5}$ or NO_2 resulted in similar RRs (e.g., for L_{den} RR 1.09 [CIs, 0.96–1.24] and 1.11 [CIs, 0.97–1.27], respectively). Due to their high correlation (0.99), results for L_{den} and L_{night} were very similar. Including WC, BMI, or depressive symptoms in the analysis did not change the estimates substantially. Results of categorical analyses and Wald tests suggested a linear relationship between outdoor noise and T2DM. In the analysis of indoor noise exposures (n = 2,697; 233 [8.6%] incident cases of T2DM at follow-up), we found similar point estimates, but the CIs were smaller (Table 4). Sensitivity analyses excluding 560 participants who had moved between baseline and follow-up examinations led to slightly increased point estimates, for example, RR for L_{den} in the fully adjusted model (M2) was 1.14 (0.99–1.30; eTable S3; http://links.lww.com/EE/A29). Analyses considering noise variables with 10 dB higher thresholds for L_{den} (55 dB) and L_{night} (45 dB) also showed higher RRs, for example, 1.15 (0.95–1.39) for L_{den} (eTable S4; http://links.lww.com/EE/A29). Analyses using noise categories showed increasing point estimates with higher noise levels. However, CIs were very large (eTable S5; http://links.lww.com/EE/A29). Effect estimates were higher for physically active ($P = 0.01$) and employed participants ($P = 0.09$) than for physically inactive and pensioners/housewives/unemployed participants (eFigure S3; http://links.lww.com/EE/A29). Most interaction analyses did not yield clear results due to wide CIs, specifically for effect modification by annoyance.

Discussion

In our population-based study, we found a positive association between road traffic noise exposure and incident T2DM. This association was independent of concurrent AP exposure. We observed similar point estimates with smaller CIs in an analysis with indoor noise exposure in a reduced sample. Sensitivity analyses with different noise thresholds and subgroups supported our conclusions.

Pathomechanisms

A large body of evidence has accumulated on the effects of noise on health.[35] The activation of the autonomic nervous system and the HPA axis are main components of an unspecific stress response, which in turn induces pathophysiological metabolic mechanisms in several organ systems (Münzel et al. 2016a).[36] Metabolic dysregulation promotes the secretion of the adrenal glucocorticoid cortisol. Besides an increase in blood pressure, viscosity, and clotting, chronically elevated glucocorticoid levels may in particular inhibit pancreatic insulin secretion and decrease insulin sensitivity in skeletal muscle, liver, and adipose tissue.[36] The contribution of acute inflammation processes and oxidative stress is still under discussion.[36,37] Experimental studies in rats underscore the role of stress-induced responses on the metabolic system, mediated by inflammatory processes: Exposure to noise was related to increased levels in inflammatory markers, elevated glucocorticoid levels, and decreased hepatic insulin sensitivity.[38–40] A recent toxicological study in mice[39] observed reduced weight gain and adipose tissue gain in mice chronically exposed to noise compared to mice without noise exposure. However, noise-exposed mice had increased blood levels of free fatty acids, indicating a poor glycemic control, probably induced by high levels of stress hormones. A second pathway emphasizes the role of sleep disturbances, which may be partly caused by nighttime traffic noise. Noise may provoke both unconscious and conscious physiologic arousals at night, causing sleep disturbances that lead to multiple physiological, psychological, and social health consequences.[41] Specifically, sleep deprivation is known to alter energy metabolism, resulting in dysregulated glucose and appetite regulation, both representing potential mediators in the development of diabetes.[8,36,42]

Comparison to other studies

Three recently published prospective cohort studies investigating the association between road traffic noise and incident T2DM showed similar or even more pronounced results in comparison to ours.[5,6,43] In contrast, a study investigating the effect of aircraft noise on pre-diabetes and T2DM reported unclear associations.[10] This might be a consequence of different noise patterns of aircraft noise compared to road traffic noise. Second, Eriksson et al.[10,13] also included psychological distress which could have acted as a mediator and therefore attenuated risk estimates. In line with our results, two studies[10,13] observed increased effect estimates for those participants who did not move during the study period.

Table 4

Relative risks with 95% CIs for T2DM per 10 dB increase of outdoor and indoor noise exposure in the Heinz-Nixdorf-Recall study population (n = 2,697)

	L_{DEN}		L_{NIGHT}	
	Outdoor	Indoor	Outdoor	Indoor
Crude	1.12 (0.97–1.29)	1.11 (1.01–1.21)	1.12 (0.97–1.29)	1.10 (0.99–1.23)
M1[a]	1.10 (0.95–1.27)	1.10 (1.00–1.20)	1.10 (0.95–1.27)	1.11 (1.00–1.23)
M2[b]	1.10 (0.95–1.27)	1.11 (1.01–1.21)	1.10 (0.95–1.27)	1.11 (1.00–1.24)
Multipollutant analyses				
M2 + $PM_{2.5}$	1.09 (0.93–1.25)	1.10 (1.01–1.21)	1.10 (0.94–1.27)	1.11 (1.00–1.24)
M2 + NO_2	1.11 (0.96–1.30)	1.11 (1.01–1.22)	1.11 (0.96–1.30)	1.12 (1.01–1.24)
Mediation analyses				
M2 + WC	1.08 (0.93–1.24)	1.07 (0.98–1.17)	1.08 (0.93–1.24)	1.09 (0.98–1.20)
M2 + BMI	1.09 (0.95–1.26)	1.08 (0.98–1.18)	1.09 (0.95–1.26)	1.08 (0.98–1.20)
M2 + depressive symptoms	1.10 (0.95–1.27)	1.11 (1.01–1.21)	1.10 (0.95–1.27)	1.11 (1.00–1.24)

[a]Adjusted for age and sex.

[b]Additionally adjusted for education and neighborhood unemployment rate.

[c]Additionally adjusted for nutrition, alcohol consumption, smoking status, pack-years, SHS, physical activity (yes/no), weekly metabolic physical activity.

$PM_{2.5}$, fine particulate matter; NO_2, nitrogen dioxide.

Mediating factors

The evidence base of overweight/obesity being a possible mediator for the association between road traffic noise and T2DM remains conflicting, with several epidemiological studies observing positive associations between noise and the obesity markers BMI and/or WC[10,13] or both,[11] while others found no associations for BMI[10,12] or any markers of obesity.[13] Our study indicates a minor mediating role of obesity assessed by WC as a marker of central adipose tissue or BMI, with hardly reduced effect estimates in the models adjusted for WC or BMI. Another factor influencing the relationship between noise and T2DM might be high depressive symptoms through annoyance, sleeping disorders, and/or several physiological stress effects: A depression-related activation of the autonomic nervous system and the HPA axis may promote inflammatory processes which could contribute to the development of T2DM.[44] The evidence base for the link between noise and depression is very limited, while the evidence regarding the association between depression and T2DM is conflicting.[41,42] In our study, there was no sign of high depressive symptoms mediating the association between road traffic noise and T2DM.

Noise exposure in the context of AP

While the underlying pathomechanisms of noise and AP with regard to metabolic health effects overlap to some extent, they differ in several ways. Exposure to AP and noise both increase the activation of the nervous system able to induce metabolic imbalance, but noise perception partly represents a psychological stressor, whereas AP acts without major personal perception. Furthermore, originating from traffic as a common source, road traffic noise and AP are highly interrelated, due to diverging dispersion patterns. Although AP dispersion depends highly on meteorological conditions, noise is influenced strongly by noise barriers and buildings. Specifically, the building density influences correlations of noise and AP with street canyons, leading to higher correlations.[43] Furthermore, traffic attributes as volume, speed, and vehicle type lead to different dispersion patterns.[15,43] Two review articles point out the need to disentangle these potentially mutually confounded exposures.[15,44] In our study, participants were affected by noise and AP differently with only a moderate correlation. Upon mutual adjustment, estimates remained stable, indicating independence of noise effects from AP in our study area.

Indoor noise exposure and T2DM

Indoor noise exposure may better reflect the true personal exposure and is less correlated with ambient AP exposure. While a few studies have analyzed indoor noise exposures with cardiovascular and metabolic health outcomes, to our knowledge, there is no other study investigating indoor noise exposures with T2DM. One cross-sectional study in Spain focused on noise-related hypertension and blood pressure.[14] In this study area, outdoor road traffic noise and ambient AP were highly correlated, leading to instable results in mutually adjusted regression analyses. However, when using indoor noise estimates, they found more consistent associations for indoor noise than for outdoor noise exposure. In comparison, our outdoor noise exposures are less correlated with AP exposures than in Foraster's study (0.37 vs. 0.75), which may explain why our indoor and outdoor noise exposure-related RRs in the two-pollutant models are similar. Importantly, both Foraster's and our study observed more precise effect estimates when using indoor noise exposure estimates. Similarly, a Swiss study by Eze et al.[5] observed stronger associations between road traffic noise and T2DM in participants with bedrooms facing the street or sleeping with open windows.[5] Another study investigating the association between road traffic noise and markers of obesity found positive associations for the subset of participants with bedrooms facing a road.[13] Overall, our study and the other studies mentioned above suggest that derived indoor noise estimates may reduce exposure estimation error and may be a more precise marker for the actual noise exposure of individuals than outdoor noise and may help disentangle overlapping effects of ambient AP and ambient noise, specifically in situations of high correlation.

Strengths and limitations

A strength of our study is the prospective design in a population-based cohort with detailed assessment of demographic and lifestyle factors. In addition, we were able to use both indoor and outdoor noise variables for this analysis. We further were able to use two-exposure models with both PM and NO_2. One limitation with regard to our results is that our study had limited statistical power to find significant associations between noise and T2DM. Another limitation is that information on family history of diabetes and/or metabolic diseases was not available. Furthermore, we had no information on hearing aid use or aural deficits among our participants. In addition, we lacked information on traffic noise from railway traffic. Aircraft noise was not included in this analysis, because only a very small part of the study population (less than 1%) was estimated to be exposed to elevated noise levels from aircraft traffic. Moreover, indoor noise models have not been validated yet. We also had no information on noise exposure at work or time spent at the residence.

Finally, a possible selection effect toward healthier and better-educated participants at baseline and a possible healthy survivor effect may have biased our effect estimates.

Conclusions

Our analyses of a population-based prospective cohort study suggest that long-term exposure to indoor and outdoor road traffic noise may increase the risk of developing T2DM, independent of AP exposure. Using estimated indoor noise exposures derived from individual apartment information improves estimation of noise effects

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Conflict of interest statement

The authors declare that they have no conflicts of interest with regard to the content of this report.

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