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Outdoor residential noise exposure and sleep in preadolescents from two European birth cohorts

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ABSTRACT

Objective: To examine whether outdoor residential exposure to annual average road traffic and multiple (i.e., road traffic, railway, aircraft, industry) noise levels is related with preadolescents' sleep using maternal-reported and wrist-actigraphy data in two European birth cohorts.
Methods: This cross-sectional study used data of 1245 preadolescents from the Dutch Generation R Study and 232 from the Spanish INMA-Sabadell cohort with a mean age of 12.3 years old. We used noise maps to assess average outdoor road traffic and multiple noise levels (day-evening-night noise indicator, L_{DEN}) at each child's residential address for the year before the sleep assessment. Sleep disturbances were reported by mothers through the Sleep Disturbance Scale for Children and objectively recorded using GeneActiv wrist-actigraphy during seven subsequent days. Linear and Poisson regression models adjusted for several potential confounding variables were performed.
Results: The mean (SD) exposure to road traffic noise was 53.2 dB (7.3) in the Generation R Study and 61.3 dB (5.9) in the INMA-Sabadell cohort. Exposure to road traffic was related with reduced total sleep time and longer wake after sleep onset (e.g. −3.62 min (95%CI -6.87; −0.37) and 6.88 min (95%CI 1.15; 12.61) per an increase of 10 dB in road traffic noise, respectively) collected by wrist-actigraphy. We observed no association between road traffic exposure and maternal-reported sleep disturbances. Results were similar for multiple noise exposure.
Conclusions: These findings indicate that sleep may be compromised for preadolescents living in areas highly exposed to outdoor residential noise. Future studies using longitudinal designs to further explore these associations during the different stages of sleep development across childhood and adolescence are warranted. Also, wrist-actigraphy measurements which provide more accurate information and may be complementary to the parental- and self-reported data should be considered.

1. Introduction

In recent decades, the increase in population growth rates has resulted in nearly half of the current world population living in urbanized environments (United Nations, 2016). In urban areas, exposure to environmental noise, especially road traffic noise, is an important and growing public health problem (Salter et al., 2015). It has been estimated that more than 100 million European citizens are exposed to an average daily noise level (day-evening-night noise indicator, L_{DEN}) from road traffic of at least 55 deciBels (dB) (European Environment Agency, 2020). Other prevalent sources of environmental noise in Europe are railway, aircraft, and industry noise (European Environment Agency, 2020). The World Health Organization (WHO) established different noise recommendations based on the individual noise sources and the noise indicators. For example, WHO recommends reducing noise levels to 53 dB for L_{DEN} noise exposure and to 45 dB for night exposure (night-time noise indicator, L_{NIGHT}) for road traffic noise (World Health Organization, 2018).

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Sleep is an essential biological process that serves several vital functions, including promotion of neuroplasticity and neural development (Meerlo et al., 2015). Since these neural processes occur from early life through adolescence, sleep may be particularly important during these life stages (Rice and Barone, 2000). Sleep disruption has been related with numerous short- and long-term health consequences (Medic et al., 2017). Short-term consequences include increased stress responsivity, somatic problems, cognitive, memory, and performance deficits as well as emotional and behavioral problems. Long-term consequences of sleep disruption include hypertension, dyslipidemia, cardiovascular diseases, weight related health issues, metabolic syndrome, and diabetes mellitus type 2. Several studies have linked environmental noise exposure to higher sleep disturbances as well as shorter sleep time and quality of sleep in adults (Basner and McGuire, 2018; Evandt et al., 2017; Janson et al., 2020). However, the relationship between environmental noise and its influence on children's sleep is less well-known (Kamp et al., 2015). Some previous studies reported that children aged 7–14 exposed to higher levels of outdoor nocturnal road traffic noise levels showed more self- and parental-reported sleep disturbances (Öhrström et al., 2006; Skrzypek et al., 2017; Tiesler et al., 2013; Weyde et al., 2017). However, there are existing studies that found no association in children of similar ages exposed to outdoor daily average noise levels from road traffic (Lee et al., 2021) or in infants during their first year of life exposed to outdoor nocturnal transportation noise (i.e., road, railway, and aircraft) (Blume et al., 2022). To the best of our knowledge, only two prior studies using actigraphy to evaluate physiological sleep measures in children have found no associations with exposure to road traffic (Öhrström et al., 2006) or transportation noise (Blume et al., 2022).

Overall, research examining whether environmental noise from road traffic is related to sleep disturbances in children is inconclusive. Wrist-actigraphy, which can provide valuable and complementary information alongside parental- or self-reports, has been scarcely used. Also, previous literature has mostly ignored other noise sources such as railway, aircraft, or industry, which could play a different role in sleep patterns. It has been suggested that aircraft and railway noise exposures are more disturbing than road traffic noise, and may last longer than road traffic noise events, which may be too short to be perceived by the individuals and fail to wake them up (Basner et al., 2011). Additionally, the majority of the population is exposed to more than one noise source, and, while individual source limit values may not be exceeded, the overall noise exposure may be greater due to the cumulative effects of exposure to multiple noise sources. Thus, this study aims to investigate the association between road traffic and multiple noise exposure (i.e. road, railway, aircraft, and industry) and sleep, using maternal-reported and wrist-actigraphy data in preadolescents from two birth cohorts in Europe.

2. Methods

2.1. Population and study design

For this cross-sectional study, data from the Dutch Generation R Study (Kooijman et al., 2016) and the Spanish INfancia y Medio Ambiente (INMA) Project (Guxens et al., 2012) were used. The Generation R Study includes a multi-ethnic population birth cohort of 9610 pregnancies (Kooijman et al., 2016). Mothers were included in the study if they had an expected date of delivery between April 2002 and January 2006 and lived in the study area of Rotterdam, the Netherlands. The INMA Project is a network of population-based birth cohorts established in several regions of Spain following a common protocol. In the present study, we included the INMA-Sabadell cohort because noise maps were available only in this cohort. The cohort includes 775 pregnant women and their children residing in the city of Sabadell (Catalonia, Spain) who visited the public health centre of Sabadell for a first trimester ultrasound examination between July 2004 and July 2006. Mothers were included in the study if they were 16 years or older, had a singleton pregnancy, and intended to deliver at the reference hospital. Exclusion criteria were participation in a reproduction programme or having communication problems. We included a total of 1477 children from both cohorts, 1245 from Generation R and 232 from INMA-Sabadell, with information on environmental noise exposure and sleep disturbances or physiological sleep measures at mean age of 12.3 years old (Supplementary Material Fig. S1). Ethical approval was obtained before recruitment from the Medical Ethical Committee of Erasmus MC, University Medical Centre Rotterdam, in accordance with Dutch law for the Generation R Study and from the Clinical Research Ethical Committee of the Municipal Institute of Healthcare (CEIC-IMAS) for the INMA-Sabadell cohort. We obtained written informed consent from parents in both cohorts and from all the participants in the Generation R Study.

2.2. Noise exposure assessment

We used noise maps created in 2012 for the municipalities of Rotterdam, Maassluis, Rozenburg, Schiedam, and Vlaardingen in the Netherlands and of Sabadell in Spain to estimate the outdoor exposure to residential annual average levels of environmental noise. These maps met the requirements of the European Environmental Noise Directive (European Environmental Noise Directive, 2002). For the Generation R Study, noise was modelled using the standardized Dutch calculation methods ('Standaard Rekenmethoden', SRM), including surfaces polygon, buildings, barriers, slope, crossings, roundabouts as well as the corresponding emission sources for each of the specific models. Briefly, in the SRM method, the noise level at the geocoded point is determined by the noise emission of the source and other factors that denote the attenuation from source to receiver due to geometric spreading, air absorption, ground impedance, noise barriers as well as wind directions and temperature gradients (Supplementary Methods S1). For the INMA-Sabadell cohort, noise was measured using a street categorization method taking into account the different types of street and land uses. Additionally, street geometry, presence of activities, type of traffic, and traffic flow were also considered to calculate the noise level. Both maps were developed to estimate the noise levels at a height of 4 meters (m) at the most exposed façade of the residential addresses. Environmental noise exposure for both cohorts was calculated at each participant's geocoded address where they lived at during the year prior to the sleep assessment. If more than one address was available, the amount of days that the participant spent at each address was considered to derive the average noise levels for each participant of the year prior the sleep assessment. For the Generation R Study, we performed an intersection of the buildings noise data from the maps with the geocodes. In cases where the geocode was outside the noise building, but within 50 m, it was assigned to the closest building. For the INMA-Sabadell cohort, we calculated the noise level of the street closest to the geocode at a distance of 50 m. Using the residential noise levels, we calculated exposure to road traffic for both cohorts. In the Generation R Study, exposure to multiple noise in which railway, aircraft, and industry noise sources was additionally considered by adding up the four different noise sources in the sound pressure scale as indicated in the formulas detailed in Supplementary Material Methods S2. For both cohorts, noise maps have integer resolution for road traffic noise and for the other noise sources in the Generation R Study. However, noise maps for multiple noise have decimal resolution in the Generation R Study. Additionally, in both study areas, noise was subtracted from the maps in categories of 1 dB. For both road traffic and multiple noise, we calculated the day-evening-night EU noise indicator (L_{DEN}) using the formulas described in Supplementary Material Methods S2. L_{DEN} represents the A-weighted average sound level over the entire 24-h day with penalties for the evening (+5 dB) and the night (+10 dB), as suggested by the Environmental Noise Directive to account for the expected greater health effects of the evening and night-time periods. The indicators

L_{DAY}, $L_{EVENING}$, and L_{NIGHT} were defined as the A-weighted mean sound levels obtained during the day (07:00 to 19:00 for Generation R and 07:00 to 21:00 for INMA-Sabadell), the evening (19:00 to 23:00 for Generation R and 21:00 to 23:00 for INMA-Sabadell), and the night (23:00 to 07:00 for both cohorts), respectively (European Environmental Noise Directive, 2002). We used the L_{DEN} indicator instead of L_{NIGHT} since children generally go to bed earlier in the evening, when road traffic noise levels are usually higher than during the night (Skinner and Grimwood, 2000). From now on, we will refer to road traffic L_{DEN} and multiple L_{DEN} as road traffic noise exposure and multiple noise exposure.

2.3. Sleep disturbances

Children's sleep disturbances were reported by mothers through the Sleep Disturbance Scale for Children (SDSC) in both cohorts (Bruni et al., 1996). SDSC is a 26-item scale validated questionnaire that provides a standardized measure of sleep disturbances in children and adolescents for the previous six months. The items were grouped into six components which evaluated the most common sleep disturbances during childhood and adolescence. In this study, we used the following SDSC components: i) problems with initiating and maintaining sleep, ii) excessive somnolence, and iii) arousal problems (i.e. partial awakening from deep to light sleep, or from sleep to a state of being awake in which the subjects are partially or totally unconscious). We treated the first two components (problems with initiating and maintaining sleep (range = 0–35) and excessive somnolence (range = 0–25)) as continuous variables in which a higher rating indicates more sleep disturbances. Arousal problems were categorized due to its skewed distribution in our study population (presence of arousal problems (yes) vs. no arousal problems (no)).

2.4. Physiological sleep measures

Sleep was objectively measured with a GeneActiv tri-axial wrist accelerometer placed on the non-dominant wrist during seven consecutive days in both cohorts (Cabré-Riera et al., 2021; Koopman-Verhoeff et al., 2019a; Koopman-Verhoeff et al., 2019b). The accelerometers recorded raw data of sleep/wake measurements, that were processed using the R-package GGIR (van Hees et al., 2015). Using this method, the following physiological sleep measures were obtained for each day: total sleep time (in hours), sleep efficiency (in %), sleep onset latency (in minutes), and wake after sleep onset (in minutes). Total sleep time refers to the total amount of time asleep during the night, extracting the time scored as awake in between. Sleep efficiency is defined as the ratio of total sleep time to the total time in bed. Sleep onset latency is the time a child needs to fall asleep, indicating the time from being fully awake to falling asleep. Wake after sleep onset is the amount of time a child spends awake, starting from the time they fall asleep until the time they become fully awake and do not attempt to fall asleep again. Finally, we calculated the mean of each of the preceding physiological sleep measures over the seven days.

2.5. Potential confounding variables

Potential confounding variables were defined a priori using a direct acyclic graph (Hernán et al., 2002) based on updated knowledge of the scientific literature and data availability in each cohort (Supplementary Material Fig. S2). In both cohorts, these variables were collected via questionnaires and instruments completed by the parents. We included information on preadolescent's sex (male or female) and age (in years), parental ages at enrollment (in years), country of birth (country of the cohort vs. others), education level (low: no education, unfinished primary or primary; medium: secondary; high: university degree or higher), social class based on occupation (low: semi-skilled/unskilled; medium: skilled manual and non-manual; high: managers/technicians) and family status (dual or single parent), maternal parity (nulliparous vs. multiparous)), smoking during pregnancy (yes or no), and alcohol use during pregnancy (yes or no) for both cohorts.

2.6. Statistical analyses

We applied a square root transformation to best approximate the normality of the residuals for the following variables: problems with initiating and maintaining sleep, excessive somnolence, and sleep onset latency. After ensuring that assumptions of the linear regressions models (i.e., normality residual, linearity between exposure and outcomes, homoscedasticity, no collinearity) were met, we applied linear regression models to assess the association of road traffic noise exposure with problems with initiating and maintaining sleep, excessive somnolence, total sleep time, sleep efficiency, sleep onset latency, and wake after sleep onset. We performed Poisson regression models with robust variance to avoid overdispersion to assess the relationship between road traffic noise exposure with problems of arousal. We calculated prevalence ratios (PR) rather than odds ratios (OR), because OR can overestimate PR, especially when the prevalence of the outcome is moderate or high (prevalence rates above 10%) in cross-sectional studies (Espelt et al., 2016). Associations were analyzed performing pooled analysis that combined data from both cohorts when we assessed the exposure to road traffic noise. We adjusted the statistical models for cohort and all potential confounding variables described in the previous section.

As sensitivity analyses, we assessed i) the association between road traffic noise exposure and each of the sleep outcomes restricted to children living in the basement, ground, or first floor to reduce the measurement error of noise exposure; ii) the associations between road traffic noise exposure and each of the sleep outcomes stratified by cohort; and iii) the association between multiple noise exposure with all the sleep outcomes in the Generation R Study.

To increase the validity of the results and limit attrition bias, we performed multiple imputation of missing values of potential confounding variables by using chained equations to generate 25 complete datasets for each subset of the analysis and separately for each cohort (Spratt et al., 2010) (Supplementary Material Table S1). The percentage of missing data was less than 30% for all the confounding variables, except for paternal social class in the Generation R Study which was approximately 33%. The imputed datasets showed similar distributions to the observed datasets (data not shown). Preadolescents from the Generation R Study (n = 1245) included in the analysis were more likely to have older parents, parents from the Netherlands, and with higher education and social class than children who were not included in the analysis (n = 8365). Preadolescents from the INMA-Sabadell cohort (n = 232) included in the analysis had similar characteristics to those who were not included (n = 543), with the exception of parental country of birth and paternal age (Supplementary Material Table S2). Inverse probability weighting was also used to correct for the losses to follow-up in both cohorts, i.e. to account for potential selection bias when including only participants with available data compared with the full cohort recruited at pregnancy (Weisskopf et al., 2015; Weuve et al., 2012). The variables used to generate the weights can be found in Supplementary Material Table S3.

We used Stata version 14 (StataCorporation, College Station, TX) to perform the statistical analyses.

3. Results

3.1. Descriptive analysis

In the INMA-Sabadell cohort, 32.2% of preadolescents reported arousal problems compared to 20.4% in the Generation R Study (Table 1). Total sleep time was an average of between 7.2 and 7.5 hours and sleep efficiency was around 85% in both cohorts. Sleep onset latency and wake after sleep onset were weakly and positively correlated with

Table 1
Participant characteristics of the INMA-Sabadell cohort and Generation R Study.

Characteristics	INMA-Sabadell (n = 232)	Generation R (n = 1245)
Sleep disturbances		
Disorders of initiating and maintaining sleep[a]	2.5 (2.4)	5.5 (3.3)
Disorders of excessive somnolence[b]	2.0 (2.2)	3.2 (2.4)
Disorders of arousal (yes vs. no)	32.2	20.4
Physiological sleep measures		
Total sleep time (hours)	7.2 (0.6)	7.5 (0.8)
Sleep efficiency (%)	85.0 (4.4)	84.6 (5.8)
Sleep onset latency (minutes)	7.7 (12.4)	41.5 (35.7)
Wake after sleep onset (minutes)	40.3 (22.4)	79.0 (42.5)
Preadolescents' characteristics		
Sex (male vs. female)	51.7	48.0
Age at sleep questionnaire assessment (years)	11.1 (0.6)	12.7 (1.5)
Maternal characteristics		
Age at enrolment (years)	31.8 (4.3)	32.2 (4.2)
Country of birth (country of cohort vs. others)	92.0	81.1
Education level during pregnancy		
Low	25.5	2.7
Medium	40.6	35.4
High	33.9	61.9
Social class during pregnancy		
Low	23.3	1.3
Medium	32.2	27.4
High	44.5	71.3
Parity (nulliparous vs. multiparous)	55.5	56.7
Smoking use during pregnancy (no vs. yes)	85.6	87.1
Alcohol consumption during pregnancy (no vs. yes)	76.6	44.8
Paternal characteristics		
Age at enrolment (years)	34.0 (5.3)	34.6 (5.1)
Country of birth (country of cohort vs. others)	91.2	83.5
Education level during pregnancy		
Low	34.8	3.6
Medium	43.2	35.6
High	22.0	60.8
Social class during pregnancy		
Low	20.1	5.7
Medium	18.0	17.1
High	61.9	77.2
Household characteristics		
Family status (dual vs. single parent)	98.5	94.4

Values are percentages for categorical variables and mean (standard deviation) for continuous variables.
[a] Higher scores indicate more sleep disturbances. Score range: 0–35.
[b] Higher scores indicate more sleep disturbances. Score range: 0–25.

disorders of initiating and maintaining sleep (r = 0.16 and 0.10, respectively) (Supplementary Material Table S4). Average road traffic noise exposure levels were 53.2 dB (standard deviation (SD) 7.3) in the Generation R Study and 61.3 dB (SD 5.9) in the INMA-Sabadell cohort. Multiple noise exposure levels were 54.4 dB (SD 6.7) in the Generation R Study (Table 2). Correlation between road traffic and multiple noise exposure was 0.94 in the Generation R Study (data not shown). Additional descriptive statistics of the noise exposure levels for both cohorts are shown in Table 2 and Supplementary Material Fig. S3. Descriptive participant characteristics of the study population can be found in Table 1. The average age of preadolescents in the Generation R Study was 12.7 years, ranging from 10.3 to 15.6 years old. In the INMA-Sabadell cohort, the mean age was 11.1 years, ranging from 9.8 to 12.7 years old. Most parents in these cohorts were from the country of the cohort (Dutch or Spanish), from a high social class (e.g., 71.3% and 44.5% of the mothers in Generation R Study and INMA-Sabadell cohort, respectively), and most of the mothers did not smoke during pregnancy (87.1% and 85.6% in Generation R Study and INMA-Sabadell cohort, respectively). However, the education level of both parents differed

Table 2
Descriptive statistics of the noise exposure levels in the INMA-Sabadell cohort and Generation R Study.

	Mean	SD	p25; p75	Min.	Max.
INMA-Sabadell (N = 232)					
Road traffic noise (L_{DEN})[a] (dB)	61.3	5.9	58.0; 65.0	46.0	76.0
Generation R (N = 1245)					
Road traffic noise (L_{DEN})[a] (dB)	53.2	7.3	48.0; 58.0	40.0	72.0
Multiple noise (L_{DEN})[b] (dB)	54.4	6.7	49.5; 58.8	40.0	72.0

Abbreviations: dB, decibels; Min., minimum; Max., maximum; p25, 25th percentile; p75, 75th percentile; SD, standard deviation.
[a] Residential outdoor annual average noise levels for the 24 h of the day from road traffic.
[b] Residential outdoor annual average noise levels for the 24 h of the day in which road traffic, railway, aircraft, and industry sources are considered.

between the cohorts, with most of the parents having a high education level in the Generation R Study (e.g., 61.9% of the mothers) and a medium education level in the INMA-Sabadell cohort (e.g., 40.6% of the mothers).

3.2. Association between road traffic noise exposure, sleep disturbances, and physiological sleep measures

Road traffic noise exposure was not associated with problems of initiating and maintaining sleep, excessive somnolence, and arousal problems (0.02 points (95% confidence interval (CI) −0.03; 0.08), −0.04 points (95% CI -0.10; 0.02), and prevalence ratio (PR) 1.03 (95% CI 0.89; 1.18) per 10 dB increase in road traffic noise, respectively) (Table 3).

When we assessed the physiological sleep measures, we found that greater road traffic noise exposure was associated with reduced total sleep time (−3.62 min (95% CI -6.87; −0.37) per 10 dB increase in road traffic noise) (Table 4). However, road traffic noise exposure was not associated with the rest of physiological sleep measures: sleep efficiency, sleep onset latency, and wake after sleep onset (−0.12% (95% CI -0.53; 0.28), 0.09 min (95% CI -0.09; 0.27), and 1.42 min (−1.60; 4.44) per 10 dB increase in road traffic noise, respectively).

3.3. Sensitivity analysis

Analyses restricted to preadolescents who were living in the basement, ground, or first floor did not show relevant differences with the main analysis of the study population when sleep disturbances were explored (Table 3). However, we found that road traffic was more strongly associated with shorter total sleep time (−5.63 min (95% CI -10.98; −0.29) per 10 dB increase in road traffic noise). Additionally, road traffic noise exposure was associated with longer wake after sleep onset (6.88 min (95% CI 1.15; 12.61) per 10 dB increase in road traffic noise) when analysis were restricted to those preadolescents (Table 4).

When these associations were stratified by cohorts, most associations remained (Supplementary Material Tables S5 and S6). However, we found that road traffic exposure for preadolescents who were living in the basement, ground, or first floor were associated with reduced sleep efficiency in the INMA-Sabadell cohort (e.g. −2.02% (95% CI -3.87; −0.18) per 10 dB increase in road traffic noise) and with longer wake after sleep onset in the Generation R Study (e.g. 9.15 min (95% CI 2.69; 15.60) per 10 dB increase in road traffic noise) (Supplementary Material Tables S5 and S6).

Effect estimates of the associations between multiple noise exposure and all the sleep outcomes in the Generation R Study were similar than those of the associations with road traffic noise exposure (Supplementary Tables S5 and S6).

Table 3
Fully adjusted cross-sectional associations between a 10 dB increase in road traffic noise exposure and sleep disturbances score in preadolescents.

		Disorders of initiating and maintaining sleep[a]	Disorders of excessive somnolence[a]	Disorders of arousal (yes vs. no)
	N	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*PR (95% CI)*
Road traffic noise (L_{DEN}[b])				
Overall	1432	0.02 (−0.03; 0.08)	−0.04 (−0.10; 0.02)	1.03 (0.89; 1.18)
Living in the basement, ground, or first floor	460	0.08 (−0.02; 0.18)	−0.01 (−0.12; 0.10)	0.96 (0.74; 1.24)

Coefficients and 95% confidence intervals (CI) were obtained by linear and prevalence ratio and 95% CI by Poisson with robust variance regression models. All models were adjusted for cohort, preadolescent sex and age at sleep questionnaire assessment, parental age, country of birth, education, social class, maternal parity, smoking and alcohol during pregnancy, and family status.
Abbreviations: CI, confidence interval; dB, decibels; PR, prevalence ratio.
[a] Values were square root transformed.
[b] Residential outdoor annual average noise levels for the 24 h of the day from road traffic.

Table 4
Fully adjusted cross-sectional associations between a 10 dB increase in road traffic exposure and physiological sleep measures in preadolescents.

		Total sleep time (minutes)	Sleep efficiency (%)	Sleep onset latency[a] (minutes)	Wake after sleep onset (minutes)
	N	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Coefficient (95% CI)*	*Coefficient (95% CI)*
Road traffic noise (L_{DEN}[b])					
Overall	1367	**−3.62 (-6.87; -0.37)**	−0.12 (−0.53; 0.28)	0.09 (−0.09; 0.27)	1.42 (−1.60; 4.44)
Living in the basement, ground, or first floor	432	**−5.63 (-10.98; -0.29)**	−0.22 (−0.83; 0.38)	0.21 (−0.12; 0.55)	**6.88 (1.15; 12.61)**

Coefficients and 95% confidence intervals were obtained by linear regression models adjusted for cohort, preadolescent sex and age at sleep questionnaire assessment, parental age, country of birth, education, social class, maternal parity, smoking and alcohol during pregnancy, and family status.Statistically significant associations in bold (p-value <0.05).
Abbreviations: CI, confidence interval; dB, decibels.
[a] Values are square root transformed.
[b] Residential outdoor annual average noise levels for the 24 h of the day from road traffic.

4. Discussion

The present study examined the association between outdoor residential L_{DEN} road traffic and multiple noise exposure, and maternal-reported sleep disturbances as well as physiological sleep measures in preadolescents from two birth cohorts set up in Europe. No associations were found between road traffic and multiple noise exposure and sleep disturbances reported by mothers. In contrast, actigraphy data showed that greater road traffic was related to shorter sleep duration. In addition, road traffic and multiple noise exposure were associated with longer wake after sleep onset in children who were living in the basement, ground, or first floor. Our findings were mainly driven by the Generation R Study due to the large sample size. However, road traffic noise levels were higher in the INMA-Sabadell cohort and effect estimates for some sleep outcomes were also higher when we stratified the analyses by cohort. Therefore, we could expect stronger associations if the sample size in the INMA-Sabadell cohort would have been larger.

To date, few studies have looked into the association between environmental noise and sleep in children (Blume et al., 2022; Lee et al., 2021, Öhrström et al., 2006; Skrzypek et al., 2017; Tiesler et al., 2013; Weyde et al., 2017). The results of our study were not fully consistent with previous research. Four studies found associations between outdoor residential nocturnal road traffic noise exposure and some sleep outcomes reported by the parents such as poorer sleep quality and excessive sleepiness during the day (Öhrström et al., 2006), more sleep disorders (Skrzypek et al., 2017; Tiesler et al., 2013), greater difficulty falling asleep (Tiesler et al., 2013), and shorter sleep duration, but only in girls (Weyde et al., 2017). In contrast, two studies found no evidence for a relationship between exposure to nocturnal road traffic in children aged 9–12 years (Öhrström et al., 2006) or transportation noise (i.e., road, railway, and aircraft) in infants during their first year of life (Blume et al., 2022) and sleep measured by actigraphy. In our study, we found that road traffic noise exposure was associated with total sleep time using wrist-actigraphy data, in line with one of the previous studies that found an association only when the analysis was restricted to infants without siblings (Blume et al., 2022). Overall, there is little agreement among studies, but some studies suggest a possible relationship between road traffic noise exposure and sleep in children and preadolescents.

There are some potential explanations for the differing results observed between previous studies conducted in children. First, some individual habituation to noise may occur. This happens when neurons adapt to repetitive auditory stimuli, but respond to stimuli with different physical properties and therefore process them differently (Pérez-González and Malmierca, 2014). Interestingly, Tiesler et al. reported an association between nocturnal road traffic noise at the least exposed façade and maternal-reported sleeping problems in children, and this association was stronger when models were adjusted for sleeping alone in a room (Tiesler et al., 2013). It has also been shown that infants without siblings who are therefore accustomed to lower levels of noise, may be more susceptible to nocturnal transportation noise and consequently to its adverse effects (Blume et al., 2022). Unfortunately, we did not have information if the child had slept alone or not. Second, the degree of misclassification between outdoor and indoor noise in the bedroom as well as differences in the exposure and outcomes measures used may affect the comparability of the studies (Basner et al., 2011). Third, there is evidence of an association between socioeconomic status (SES) and sleep, showing that low-SES children reported shorter sleep duration and self-reported subjective sleep disturbances (e.g. difficulty falling asleep or maintaining sleep), compared with high-SES children (Bagley et al., 2015). Parental education has also been linked to preadolescent's sleep, with earlier sleep times, shorter sleep latencies, and more regular sleep routines for their children (McDowall et al., 2017). Families with lower socioeconomic resources may have more difficulty providing an optimal sleep environment for their children. They are also more likely to live in noisy neighborhoods and in smaller and crowded dwellings. In our study, we adjusted the main analysis for several SES indicators, including parental education, parental social class, country of birth, and maternal smoking during pregnancy among others. Nevertheless, residual confounding cannot be completely

discarded. Additionally, discrepancies on the results between studies carried out in child and adult populations may be related to differences in noise sensitivity in those populations. Children seem to be 10–15 dB less sensitive to noise as compared to adults and therefore they may be less likely to awaken due to noise events than adults (Eberhardt, 1983). However, children are considered to be at particular risk due to the neural processes that occur in this stage of life, and also because they tend to have earlier bedtimes and longer periods of sleep than adults, which may coincide with periods of heavy road traffic (Gau and Merikangas, 2004).

Strengths of the present study include a large sample size compared with similar previous studies in children using physiological sleep measures, an analysis of children from two population-based birth cohorts from two different European countries, the assessment of noise exposure considering the amount of time the child lived at each geocoded address, and the availability of sleep measures using both maternal-reported and wrist-actigraphy data. We have also included information about the floor of the bedroom that could have led to more accurate noise estimations to reduce the measurement error in assessing noise exposure. Adjustments were made for many confounding variables that may be related to environmental noise exposure and sleep in preadolescents. Additionally, multiple imputation and inverse probability weighting were used in order to reduce the potential selection bias (Spratt et al., 2010; Weuve et al., 2012). Finally, we treated most of the sleep outcomes as continuous variables, to avoid outcome misclassification bias.

However, our study also has some limitations that need to be discussed. The main limitation of the study was its cross-sectional design. Longitudinal studies may be necessary to further explore whether environmental noise exposure is associated with sleep during the different stages of sleep pattern development across childhood and adolescence periods. Although reverse causality cannot be completely discarded, we do not expect that families with more sleep problems had moved to areas with higher environmental noise exposure. A further limitation is that the noise levels corresponded to estimated outdoor noise levels instead of noise levels in the bedroom. Unfortunately, as all other large epidemiological studies, we did not have this data, nor did we have information on noise insulation characteristics, if windows were left open or closed during the night, and noise from neighbors, restaurants, or cafés. Therefore, we cannot exclude the possibility of misclassification due to under- or overestimation of true noise exposure levels. Nevertheless, one of the most important sources of misclassification for long-term noise exposure is the effect of shielding due to the orientation of the bedroom towards the noise source (here mainly the street). Future studies should include data related to the child's bedroom (i.e., location of the bedroom, orientation of the windows, floor's level, etc.) in order to reduce the measurement error and provide more accurate effect estimates of the association. Only two previous studies among children considered bedroom window orientation in their analyses (Öhrström et al., 2006; Tiesler et al., 2013). In one study, an approximation of the road traffic noise levels at night was done by subtracting 10 dB when the window of the bedroom was facing a courtyard instead of the most exposed façade (Öhrström et al., 2006). They found an association between higher noise exposure at night and increased awakenings and reduced sleep quality . In the other study, Tiesler et al. also found that nocturnal road traffic noise at the least exposed façade, but not at the most exposed façade, was associated with more sleeping problems, especially with problems falling asleep, after adjustment for the orientation of the child's room window (Tiesler et al., 2013). However, these findings seems counterintuitive because bedrooms facing a quieter façade of the dwellings were exposed to lower levels of road traffic noise. Furthermore, in our study we assessed sleep disturbances reported by mothers together with physiological sleep measures. Actigraphy consistently reports more accurate data than parental questionnaires (Bauer and Blunden, 2008; Kushnir and Sadeh, 2013; Werner et al., 2008), but it cannot provide information about bedtime routines that can influence the child's sleep, which can be collected by questionnaires. A limitation of actigraphy is that since sleep parameter estimation is based on monitoring activity, absence of movement that may occur during quiet activities could be registered as sleep periods and on the other hand movements during restless sleep episodes (typical in young children) could be interpreted as sleepwalkings, biasing the sleep estimations. Another limitation is that actigraphy only reflected the sleep of a one-week period in our study. However, questionnaires also introduce limitations since they are susceptible to recall bias and parents are sometimes unaware of their children's behaviors. Therefore, parental reports and actigraphy data provide differing, but complementary information about a child's sleep habits (Holley et al., 2010). Additionally, information on children's self-reported sleep habits as well as sleep medication use were not collected and could not be included in the present study. Another limitation is that we were not able to conduct separate source analyses in the Generation R Study because the population exposed to railway, aircraft, and industry noise sources was too small to perform them. These analyses would have been interesting to further explore the effect of each noise source on children's sleep. For example, road traffic noise tends to be constant and children can habituate to it. Although constant noise exposure can alter sleep structure and continuity, habituated children will less likely consciously perceive noise events. In contrast, aircraft and railway sources are characterized by intermittent noise with higher peak noise levels and less predictability, being scored as more disturbing than road traffic noise (Basner et al., 2011). Finally, the study did not consider individual noise sensitivity which could influence the results (Potgieter et al., 2020).

5. Conclusions

In conclusion, this study indicates that long-term outdoor exposure to residential road traffic noise, the most prevalence noise source in Europe, was associated with reduced total sleep time and longer wake after sleep onset collected by wrist-actigraphy in preadolescents. Results were similar for multiple noise exposure, although most of the association was attributable to road traffic noise as it is the most predominant noise source. Road traffic or multiple noise exposures were not associated with sleep disturbances reported by mothers. Although the observed estimates were relatively small, these results might be more meaningful at the population-level due to the high prevalence of exposure to environmental noise. In future studies, efforts should be made to measure sleep longitudinally using wrist-actigraphy data, which provides more accurate and consistent information about sleep patterns of children.

Credit author statement

Laura Pérez-Crespo: conceptualization, formal analysis, methodology, writing – original draft, visualization. **Esmée Essers:** formal analysis, writing – review & editing. **Maria Foraster: conceptualization, methodology,** writing – review & editing. **Albert Ambrós:** methodology, writing – review & editing. **Henning Tiemeier:** conceptualization, writing – review & editing, funding acquisition. **Mònica Guxens:** conceptualization, methodology, writing – review & editing, supervision, funding acquisition.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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