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Association between residential exposure to road traffic noise and cognitive and motor function outcomes in children and preadolescents

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ABSTRACT

Background: Exposure to environmental noise is increasing in recent years but most of the previous literature in children has evaluated the effect of aircraft noise exposure at schools on cognition.
Objective: To assess whether residential exposure to road traffic noise during pregnancy and childhood is associated with cognitive and motor function in children and preadolescents.
Methods: The study involved 619 participants from the Spanish INMA-Sabadell cohort and 7,115 from the Dutch Generation R Study. We used noise maps to estimate the average day-evening-night road traffic noise levels at each participant's residential address during pregnancy and childhood periods. Validated tests were administered throughout childhood in both cohorts to assess non-verbal and verbal intelligence, memory, processing speed, attentional function, working memory, cognitive flexibility, risky decision-making, and fine and gross motor function. Linear models, linear mixed models, and negative binomial models were run depending on the outcome in cohort-specific analysis and combined with a random-effects *meta*-analysis. All models were adjusted for several socioeconomic and lifestyle variables and results corrected for multiple testing.
Results: Average road traffic noise exposure levels during pregnancy and childhood were 61.3 (SD 6.0) and 61.5 (SD 5.4) dB for the INMA-Sabadell cohort and 54.6 (SD 7.9) and 53.5 (SD 6.5) dB for the Generation R Study, respectively. Road traffic noise exposure during pregnancy and childhood was not related to any of the cognitive and motor function outcomes examined in this study (e.g. −0.92 (95 % CI −2.08; 0.24) and 0.20 (95 % CI −0.96; 1.35) in overall estimates of memory and fine motor function, respectively, when road traffic noise increases by 10 dB during childhood).
Conclusions: These findings suggest that child's cognitive or motor functions are not affected by residential exposure to road traffic noise. However, more studies evaluating this association at school and home settings as well as noise events are needed.

1. Introduction

Urbanization processes that occurred during the past decades may have negative impacts on human well-being and health (Wang, 2018). Exposure to environmental noise has increased as a consequence of this continued urbanization and most of the population is exposed to it on a daily basis. In Europe, environmental noise from a variety of sources, mainly road traffic, railway, aircraft, and industrial, remains a major health concern (European Environment Agency, 2020). Road traffic noise is the main source of environmental noise affecting human health

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and it has been estimated that at least 20 % of all Europeans are exposed to noise levels higher than 55 deciBels (dB) (European Environment Agency, 2020).

Previous epidemiological and experimental research has indicated a relationship of environmental noise exposure with diverse health effects (European Environment Agency, 2020; Terzakis et al., 2022; Zijlema et al., 2021). Fetuses and children are often considered vulnerable to the effects of environmental noise because fetal life and childhood are periods of rapid growth and brain maturation (Stansfeld & Clark, 2015). It has been reported that environmental noise negatively affects the brain and cognition of children and preadolescents by adversely affecting sleep, stress, learning processes (e.g., distracting child's attention from lessons), and learned helplessness (e.g., a noisy environment can negatively affect self-control and efficacy, resulting in lack of motivation) (Thompson et al., 2022). In addition, children have less developed coping strategies and less control than adults to deal with environmental noise (Dohmen et al., 2023; Stansfeld & Clark, 2015). Most research on environmental noise exposure and children's health has been carried out on aircraft noise, showing a negative impact on children's cognitive function (Baek et al., 2023; Clark et al., 2020; Terzakis et al., 2022). However, there is limited evidence on the relationship between exposure to road traffic noise with cognitive function in children. Most of the previous studies observed no evidence for the association of road traffic noise exposure with working memory in children at 6–11 years old both when noise was assessed at home and at school (Clark et al., 2020; Julvez et al., 2021; Terzakis et al., 2022). One exception is a study where road traffic noise exposure at schools, but not at residences, was associated with lower development of working memory from 7 to 10 years old (Foraster et al., 2022). Also, findings from studies assessing whether road traffic noise exposure at school, at home, or in both settings is associated with children's memory, attentional function, and verbal and non-verbal intelligence in 6–12 years old were not consistent (Bhang et al., 2018; Clark et al., 2020; Cohen et al., 1973; Foraster et al., 2022; Julvez et al., 2021; Lercher et al., 2016; Ljung et al., 2009; Sanz et al., 1993; Terzakis et al., 2022). Lastly, the association between environmental noise exposure at home and motor function has only been investigated previously in a single study in children aged 3 and 6 years but no association was found (Raess et al., 2022).

Overall, research on the relationship between exposure to road traffic noise and cognitive and motor functions showed heterogeneous results. Additionally, most studies evaluated levels of road traffic noise at school locations and were predominantly cross-sectional. Therefore, our study aims to assess the association between residential exposure to road traffic noise during pregnancy and childhood with cognitive and motor function in children and preadolescents from two population-based birth cohorts set up in two different European countries.

2. Methods

2.1. Population and study design

This longitudinal study used data from two population-based birth cohort studies: the Spanish INfancia y Medio Ambiente (INMA) Project (Guxens et al., 2012) and the Dutch Generation R Study (Kooijman et al., 2016). The INMA Project is a Spanish network of birth cohorts established following a common protocol in several regions of Spain. Considering the availability of the noise exposure maps, we included the INMA-Sabadell cohort in the present study. A total of 775 pregnant women and their children who visited the public health center of Sabadell (Catalonia, Spain) for an ultrasound in the first trimester between July 2004 and July 2006 were included in the cohort. Women eligible for the study had to be 16 years or older, pregnant with a singleton, and intending to deliver in a reference hospital. Participants in assisted reproduction programmes and those with communication issues were excluded. The Generation R Study is a prospective population-based cohort from fetal life onwards in Rotterdam, the Netherlands. This study contains a multi-ethnic population birth cohort including 9,778 pregnancies (Kooijman et al., 2016). Mothers who were living in Rotterdam and expecting delivery in April 2002 to January 2006 were eligible for the study. A total of 7,734 children were included from both cohorts, 619 from INMA-Sabadell and 7,115 from the Generation R Study, with at least one noise exposure value and a cognitive or motor function measurement (Supplementary Material Fig. S1). Ethical approval was obtained prior to recruitment from the Clinical Research Ethical Committee of the Municipal Institute of Healthcare (CIEC-IMAS) for the INMA-Sabadell cohort and from the Medical Ethical Committee of Erasmus MC, University Medical Centre Rotterdam, for the Generation R Study. We obtained written informed consent from parents in both cohorts.

2.2. Noise exposure assessment

Available noise maps developed in 2006 and 2012 for Sabadell in Spain and in 2012 and 2017 for the municipalities of Rotterdam, Maassluis, Rozenburg, Schiedam, and Vlaardingen in the Netherlands were used to estimate the annual average levels of noise at each participant's geocoded residential address. We selected these maps because they corresponded to the period from conception until the last outcome assessment in each cohort. We did not include the Generation R map for 2007 because the methodology used to develop it was different from the one used in the 2012 and 2017 maps, making the noise estimations not comparable. The maps we used complied with the requirements of the European Environmental Noise Directive (European Environmental Noise Directive, 2002). For the INMA-Sabadell cohort, noise was measured using a street categorization method considering the different types of street and land uses. Additionally, street geometry, presence of activities, type of traffic, and traffic flow were included to determine the noise level (European Environmental Noise Directive, 2002). For the Generation R Study, noise was modelled using the standardized Dutch calculation methods ('Standaard Rekenmethoden', SRM), introducing surfaces polygon, buildings, barriers, slopes, crossings, roundabouts as well as the corresponding emission sources for each of the specific models (Schreurs et al., 2010). The maps from both countries were constructed to estimate the residential noise levels at the most exposed façade at a height of 4 meters. Noise maps were available for residential exposure levels of road traffic, railway, aircraft, and industrial noise. However, in both cohorts, a small percentage of children were exposed to railway, aircraft, or industrial noise. Thus, only data related to road traffic noise was used in the present study.

To estimate road traffic noise exposure, we assigned the day-evening-night EU noise indicator (L_{DEN}) calculated using the formulas detailed in Supplementary Material Methods S1. L_{DEN} represents the A-weighted average sound level over the entire 24-hour day with penalties for the evening (+5dB) and the night (+10 dB), as suggested by the Environmental Noise Directive to take into consideration the expected greater health impact of the evening and night-time periods (European Environmental Noise Directive, 2002). The L_{DAY}, $L_{EVENING}$, and L_{NIGHT} indicators were defined as the A-weighted average sound levels assessed during the day (07:00 to 21:00 for INMA-Sabadell and 07:00 to 19:00 for Generation R), the evening (21:00 to 23:00 for INMA-Sabadell and 19:00 to 23:00 for Generation R), and the night (23:00 to 07:00 for both cohorts), respectively (European Environmental Noise Directive, 2002). The levels of L_{DEN} for both cohorts were calculated at each geocoded address that the participants had resided at during the period of interest. We assigned the noise of the street closest to the geocode at a maximum distance of 50 meters in the INMA-Sabadell cohort. In the Generation R Study, as the noise data was associated with the buildings, we performed an intersection of the buildings with the geocodes. When the geocode was outside the building, but within 50 meters, it was assigned to the closest one. Average noise levels were calculated for each participant for the pregnancy period (from conception until birth), and for different periods during childhood, depending on the outcome assessments and the cohort. For the INMA-Sabadell cohort these periods were: from birth to 4 years old, from 4 to 7 years old, from 7 to 9 years old, and from 9 to 11 years old, and for the Generation R Study: from birth to 6 years old, from 6 to 9 years old, and from 9 to 13 years old. We calculated the average noise level by taking into account the number of days that a participant spent at each address if more than one address was available.

2.3. Cognitive and motor function outcomes

Cognitive and motor functions were assessed as non-verbal intelligence, verbal intelligence, memory, processing speed, attentional function, visuomotor attention, working memory, cognitive flexibility, risky decision-making, and fine and gross motor function using several validated neurocognitive tests throughout childhood in both cohorts. Most of these outcomes were assessed at a single time point during childhood period, except non-verbal and verbal intelligence which were repeatedly measured in both cohorts. Additionally, working memory was also repeatedly measured but only in the INMA-Sabadell cohort. In order for neurocognitive tests results to be comparable between cohorts, all scores were standardized to a mean of 100 and a standard deviation (SD) of 15. Details of the tests used, outcomes calculated, and their interpretation are detailed in Table 1 and Fig. 1.

2.4. Potential confounding variables

The potential confounding variables were a priori defined with a direct acyclic graph (Hernán et al., 2002) according to the existing literature and based on data availability in each cohort. In both cohorts, these variables were collected by questionnaires completed by the parents. We included information for both cohorts on parental ages at enrollment (in years), parental countries of birth (country of the cohort vs. others), parental education level (low: no education, unfinished primary or primary; medium: secondary; high: university degree or higher), parental social class based on occupation (low: semi-skilled/ unskilled; medium: skilled manual and non-manual; high: managers/ technicians), family status (dual or single parent), maternal parity (nulliparous vs. multiparous), maternal smoking during pregnancy (yes or no), and maternal alcohol use during pregnancy (yes or no). Using hospital records, child sex was included as a covariate. Parental height (in cm) and weight (in kg) were measured or self-reported in the first trimester of pregnancy and body mass index (in kg/m^2) was calculated based on the collected weight and height data.

2.5. Statistical analyses

To enhance validity of results and minimize attrition bias, multiple imputation of missing values of potential confounding variables for each cohort was performed using chained equations where 25 complete datasets were generated and analyzed (Spratt et al., 2010) (Supplementary Material Table S1). The percentage of missing values for the confounding variables was below 30 % except for paternal education and social class in the Generation R Study which were 30.94 % and 52.48 %, respectively. The imputed datasets had similar distributions to the non-imputed datasets (data not shown).

Children included in this analysis (619 for INMA-Sabadell cohort and 7,115 for Generation R Study) were more likely to have parents that were older, from the country of the cohort (i.e., Spanish or Dutch), had a higher level of education and social class, and had mothers that consumed less alcohol during pregnancy than those not included (156 for INMA-Sabadell cohort and 2,495 for Generation R Study) (Supplementary Material Table S2). In addition, Dutch children included in this analysis (n = 7,115) had mothers that had smoked less during pregnancy, were more likely to be nulliparous, and had a dual family status compared to children from the Dutch cohort not included (n = 2,495). Hence, we used inverse probability weighting to correct for the losses to follow-up in both cohorts and accounted for selection bias by only including participants with available data rather than the entire pregnancy cohort.

After checking that the assumptions of the models (i.e., linearity between exposure and outcomes, independence, homoscedasticity, normality of the residuals) were fulfilled, we used linear regression models to assess the associations between residential exposure to road traffic noise and memory, processing speed, visuomotor attention, and fine and gross motor function in both cohorts. We also performed linear regression models to assess the association of residential exposure to road traffic noise with cognitive flexibility and risky decision-making in the INMA-Sabadell cohort, and with working memory in the Generation R Study. For the outcomes with repeated measurements throughout childhood, we performed linear mixed models, in order to increase precision, with subject as random intercept to account for the non-independence due to repeated measures of exposure and outcome. Therefore, we ran linear mixed models to assess the associations between residential exposure to road traffic noise and repeated verbal and non-verbal intelligence in both cohorts, and repeated working memory in the INMA-Sabadell cohort. Finally, we used negative binomial regression models to assess the association between residential exposure to road traffic noise and attentional function (i.e., omission and commission errors) in both cohorts. All models were adjusted for the potential confounding variables specified in the previous section. All models were first run separately per cohort; the estimates for those outcomes that were assessed in both cohorts were combined using random effects *meta*-analysis. A Cochran Q test and an I2 statistic were used to determine the heterogeneity of the estimates. Finally, analyses were corrected for multiple testing using the Bonferroni correction to a total of 74 tests (Abdi, 2007). After the correction, we obtained a new critical p-value for each association.

All analyses were conducted using Stata version 14 (StataCorporation, College Station, TX), R (version 3.6.0 R Core Team (2019)) and PostgreSQL/PostGIS (https://postgis.net).

3. Results

Study participant characteristics of the study population from both cohorts are presented in Table 2. The average age of mothers was 31.7 and 30.5 years old in the INMA-Sabadell cohort and the Generation R Study, respectively. In the INMA-Sabadell cohort, almost all mothers were Spanish (89.3 %), about half had a medium education (42.9 %), and 47.4 % were from a high social class. In the Generation R Study, most mothers were of Dutch national origin (54.1 %), about half had a high education (47.0 %), and 62.6 % were from a high social class.

Average road traffic noise levels during pregnancy were 61.3 (SD 6.0) and 54.6 (SD 7.9) dB, whereas average road traffic noise levels during childhood were 61.5 (SD 5.4) and 53.5 (SD 6.5) dB in the INMA-Sabadell cohort and the Generation R Study, respectively (Table 2). In Supplementary Material Table S3, we provided descriptive statistics on noise exposure levels for both cohorts over different periods of interest. Correlations between road traffic noise levels throughout the different time periods of study were moderate to strong (between 0.43 and 0.97), depending on the time period and the study cohort (Supplementary Material Table S4). Descriptive statistics of cognitive and motor outcomes for both cohorts are shown in Supplementary Material Table S5.

Residential exposure to outdoor road traffic noise during pregnancy or childhood was not related with non-verbal intelligence, verbal intelligence, memory, or processing speed in the unadjusted and adjusted models for the INMA-Sabadell cohort or the Generation R Study, whether examined separately or *meta*-analyzed. For example, the *meta*-analysis yielded estimates of −0.08 (95 % confidence interval (CI) −0.81; 0.65) and −0.92 (95 % CI −2.08; 0.24) when we assessed the association with verbal intelligence and memory, respectively, when road traffic noise increases by 10 dB during childhood (Table 3).

Regarding attentional function, higher residential exposure to road traffic noise during pregnancy was nominally related with less

Table 1
Details of cognitive and motor development assessment.

Cognitive and motor function domain	Test and subtest	Outcome of interest	Interpretation	Cohort	Test references
Non-verbal intelligence	MSCA: Perceptive-performance scale	Raw score	↓score; lower non-verbal intelligence	INMA-Sabadell	(MacCarthy & Cordero Pando, 2006)
	Raven Progressive Matrices	Number of correct items	↓number of correct items; lower non-verbal intelligence		(Raven, 2003)
	SON-R: Mosaics and Categories subtests	Age-standardized score	↓score; lower non-verbal intelligence	Generation R	(Laros & Tellegen, 1991)
	WISC-V: Matrix reasoning subtest	T score	↓score; lower non-verbal intelligence		(Kaufman et al., 2015)
Verbal intelligence	MSCA: Verbal scale	Raw score	↓score; lower verbal intelligence	INMA-Sabadell	(MacCarthy & Cordero Pando, 2006)
	Semantic Verbal Fluency	Number of words of animals not repeated	↓number of words; lower verbal intelligence		(Sauzéon et al., 2004)
	TVK: Receptive subtest	Percentage correct score: total correct answers divided by the total number of items answered	↓percentage correct score; lower verbal intelligence	Generation R	(Van Bon & Hoekstra, 1982)
	WISC-V: Vocabulary subtest	T score	↓score; lower verbal intelligence		(Kaufman et al., 2015)
Memory	MSCA: Memory scale	Raw score	↓score; lower memory	INMA-Sabadell	(MacCarthy & Cordero Pando, 2006)
	NEPSY-II: Memory for faces, memory for faces delayed and memory, narrative memory	Scaled score		Generation R	(Brooks et al., 2009)
Processing speed	WISC-IV: Coding and Symbol search subtests	Raw score	↓score; lower speed of information processing	INMA-Sabadell	(Kaufman et al., 2006)
	WISC-V: Coding subtest	T score		Generation R	(Kaufman et al., 2015)
Attentional function	K-CPT NEPSY-II: Auditory attention subtest	-Omission errors: Number of times the individual did not respond to a stimulus -Commission errors: Number of times that the individual respond wrongly	↑omission errors; higher inattention ↑commissions errors; lower response inhibition	INMA-Sabadell Generation R	(Conners, 2006) (Brooks et al., 2009)
	TMT-A	Time to complete the task (ms)	↑time; lower visuomotor attention	INMA-Sabadell	(Tombaugh, 2004)
	NEPSY-II: Visuomotor precision subtest	Scaled score	↓score; lower visuomotor attention	Generation R	(Brooks et al., 2009)
Working memory	N-back: 3-back subtest	-Hit Reaction Time (HRT): Mean response time for all correct answers (ms) -d': z (hit rate) – z (false alarm rate)	↑HRT ↓d'; lower working memory	INMA-Sabadell	(Pelegrina et al., 2015)
	WISC-V: Digit Span subtest	T score	↓score; lower working memory	Generation R	(Kaufman et al., 2015)
Cognitive flexibility	TMT-B	Task switching score: Time to complete the task (ms)	↑time; lower task switching capacity	INMA-Sabadell	(Tombaugh, 2004)
	TMT-A and TMT-B	Task shifting score: (Time to complete the TMT-B (ms) – Time to complete the TMT-A (ms)) / Time to complete the TMT-A (ms))	↑score; lower task shifting capacity		
Risky decision-making	Cups	Total number of risky choices made in the gain condition total number of risky choices in the loss condition sensitivity to expected value in the gain condition (i.e., number of risk-advantageous choices minus number of risk-disadvantageous choices). sensitivity to expected value in the loss condition (i.e., number of risk-advantageous choices minus number of risk-disadvantageous choices).	↓number of risky choices; higher risky decision-making ↓score; higher risky decision-making	INMA-Sabadell	(Levin et al., 2007)
Gross motor function	MSCA: Gross motor scale	Standard score	↓score; lower gross motor function	INMA-Sabadell	(MacCarthy & Cordero Pando, 2006)
	Body Coordination Test: Walking backwards subtest	number of steps the participant can take on each beam	↓number of steps; lower gross motor function	Generation R	(Kiphard, 2007)
Fine motor function	FTT	Number of taps the participant made during the measurement with the left and right hand	↓number of taps; lower fine motor function	INMA-Sabadell and Generation R	(Lezak, 1995)

Abbreviations: FTT, Finger Tapping Test; K-CPT, Conners' Kiddie Continuous Performance Test; MSCA, McCarthy Scales of Children's Ability; NEPSY-II, Developmental NEuroPSYchological Assessment Second Edition; SON-R, Snijders-Oomen Niet-verbale intelligentie Test – Revisie; TMTA, Trail Making Test Part A; TMTB, Trail Making Test Part B; TVK, Talltest voor Kinderen; WISC-IV,4th edition of Wechsler Intelligence Scale for Children-IV; WISC V, 5th edition of Wechsler Intelligence Scale for Children.

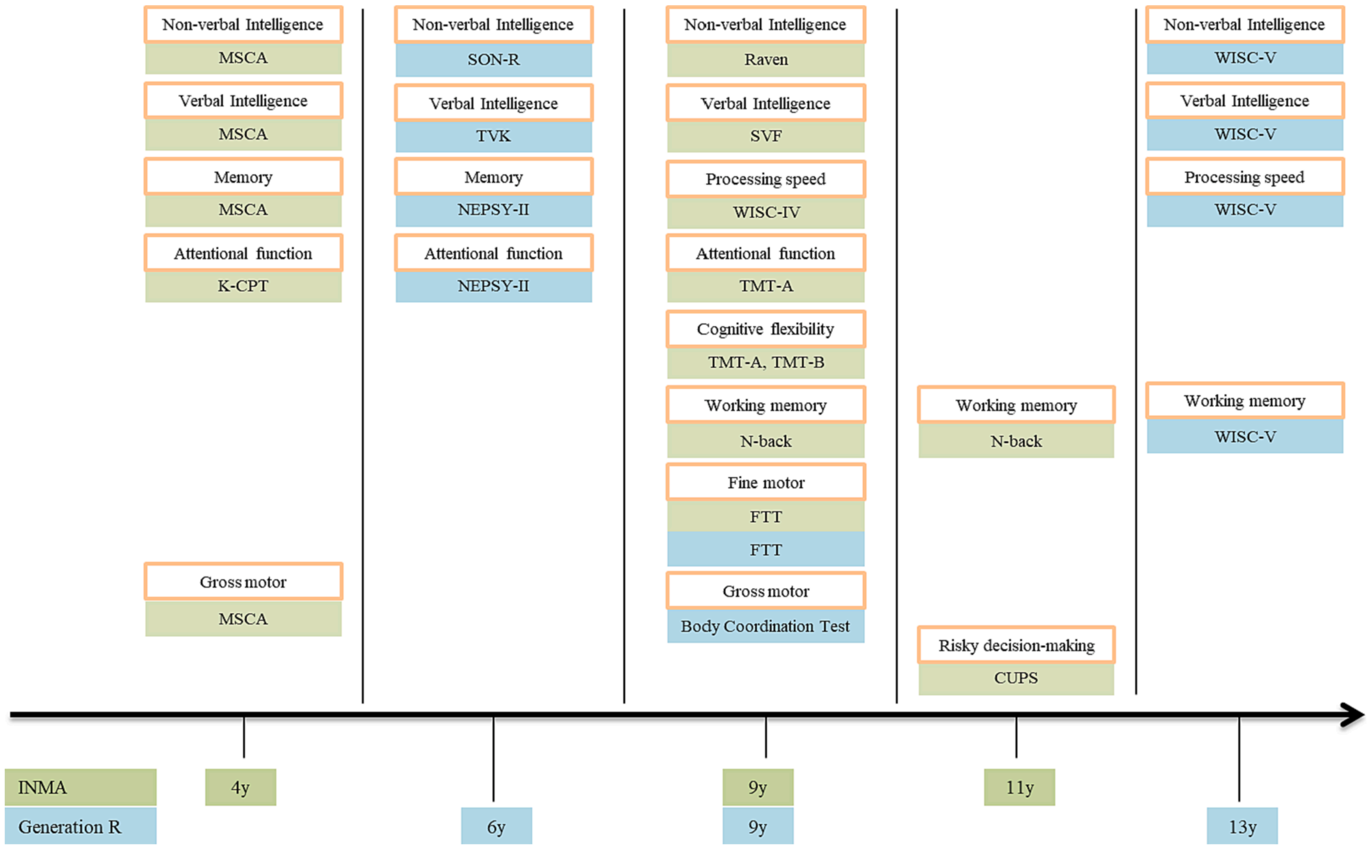

Fig. 1. Cognitive and motor outcome assessment time points and measuring instruments used in the INMA-Sabadell cohort and the Generation R Study. Abbreviations: FTT, Finger Tapping Test; K-CPT, Conners' Kiddie Continuous Performance Test; MSCA, McCarthy Scales of Children's Ability; NEPSY-II, Developmental NEuroPSYchological Assessment Second Edition; SON-R, Snijders-Oomen Niet-verbale intelligentie Test – Revisie; SVF, Semantic Verbal Fluency; TMTA, Trail Making Test Part A; TMTB, Trail Making Test Part B; TVK, Talltest voor Kinderen; WISC-IV,4th edition of Wechsler Intelligence Scale for Children-IV ; WISC V, 5th edition of Wechsler Intelligence Scale for Children.

commission errors and more omissions errors in the INMA-Sabadell cohort (Incidence Risk Ratio (IRR) 0.88 (95 % CI 0.81; 0.96) and 1.13 (95 % CI 1.01; 1.28), respectively, when road traffic noise levels increase by 10 dB during pregnancy) (Table 4). Also, we found an association between higher residential exposure to road traffic noise during childhood and less commissions errors in the INMA-Sabadell cohort (IRR 0.85 (95 % CI 0.78; 0.93) when road traffic noise levels increase by 10 dB during childhood) (Table 4). However, none of these associations survived correction for multiple testing. In addition, we found no association of residential exposure to road traffic noise during pregnancy and childhood with visuomotor attention for any of the study cohorts (e.g., 0.35 (CI −0.84; 1.54) in overall estimates of visuomotor attention when road traffic noise increases by 10 dB during childhood) (Table 4).

Fine and gross motor function were also not associated with road traffic noise exposure in any of the study cohorts (e.g. −0.07 (95 % CI −0.64; 0.50) in overall estimates of gross motor function when road traffic noise increases by 10 dB during pregnancy) (Table 5). Although we were not able to conduct *meta*-analysis to assess working memory due to discrepancies between the tests used in each cohort, similar results were found in both cohorts related to its association with road traffic noise exposure (e.g. −0.03 (95 % CI −0.13; 0.07) and −0.08 (95 % CI −0.80; 0.64) in working memory when road traffic noise increases by 10 dB during childhood in the INMA-Sabadell cohort and the Generation R Study, respectively) (Supplementary Material Table S6). A further assessment of cognitive flexibility and risky decision-making was conducted in INMA-Sabadell and no association was found with road traffic noise exposure at participants' home addresses (Supplementary Material Table S7 and S8).

4. Discussion

The present study investigated the association of residential exposure to road traffic noise during pregnancy or childhood with a large number of cognitive and motor function outcomes, some assessed repeatedly from preschool age until preadolescence in two European birth cohorts. There was no evidence that residential exposure to road traffic noise was associated with any of the outcomes studied after adjusting for several socioeconomic and lifestyle variables including parental age, country of birth, education, social class, parity, smoking, and family status.

Until now, few studies have investigated the association between road traffic noise exposure and cognitive function in children (Clark et al., 2020; Clark & Paunovic, 2018; Foraster et al., 2022; Terzakis et al., 2022; Thompson et al., 2022). Regarding non-verbal and verbal intelligence, most previous epidemiological studies also did not find a relationship with residential or school road traffic noise exposure in children aged 6 to 11 years (Clark et al., 2006; Julvez et al., 2021; Stansfeld et al., 2005), similarly to our study. In contrast, a study carried out in children aged 10–12 years found that those exposed to higher noise levels at schools, mainly to road traffic, had lower non-verbal intelligence scores than those exposed to lower noise levels (Bhang et al., 2018). Also, reading deficits were observed in children exposed to higher levels of residential noise from several sources or to higher road traffic noise at schools (Cohen et al., 1973; Ljung et al., 2009). Of note, noise levels reported in our study were lower than those reported in these previous studies (Bhang et al., 2018; Cohen et al., 1973; Ljung et al., 2009). The overall mixed findings on the association between noise exposure and non-verbal and verbal intelligence suggest that more

Table 2
Participant characteristics of the INMA-Sabadell cohort and Generation R Study.

Characteristics	INMA-Sabadell (n = 618)	Generation R (n = 7,115)
Maternal characteristics		
Age at enrolment (years)	31.7 (4.3)	30.5 (5.1)
Pre-pregnancy body mass index (kg/m^2)	23.7 (21.0; 25.3)	23.6 (20.8; 25.4)
Country of birth(country of cohort vs. others)	89.3	54.1
Education level during pregnancy		
Low	26.1	9.4
Medium	42.9	43.6
High	31.0	47.0
Social class during pregnancy		
Low	21.2	4.3
Medium	31.4	33.1
High	47.4	62.6
Parity (nulliparous vs. multiparous)	57.0	56.0
Smoking use during pregnancy (no vs. yes)	85.3	83.4
Alcohol consumption during pregnancy (no vs. yes)	78.0	59.9
Paternal characteristics		
Age at enrolment (years)	33.6 (5.0)	33.4 (5.9)
Pre-pregnancy body mass index (kg/m^2)	25.8 (23.5; 27.8)	25.3 (22.9; 27.2)
Country of birth (country of cohort vs. others)	88.9	56.7
Education level during pregnancy		
Low	34.4	7.0
Medium	42.5	40.4
High	23.1	52.6
Social class during pregnancy		
Low	22.9	8.8
Medium	18.6	23.7
High	58.5	67.5
Household characteristics		
Family status (dual vs. single parent)	98.6	87.7
Child characteristics		
Sex (male vs. female)	51.5	50.0
Noise exposure (decibels)		
Road traffic noise (L_{DEN})[1] (dB)		
Prenatal	61.3 (6.0)	54.6 (7.9)
Childhood	61.5 (5.4)	53.5 (6.5)

Values are percentages for categorical variables, mean (standard deviation) for continuous variables, and median (25th; 75th percentile) for body mass index.
Abbreviations: dB, decibels.
[1] Residential outdoor annual average noise levels for the 24 h of the day from road traffic.

research is needed. In addition, studies assessing noise levels at both school and residential locations and with a larger range of exposure levels would provide a more comprehensive exposure assessment.

Several studies have investigated the association between road traffic noise exposure and memory or working memory in children. Our results of the absence of an association were consistent with some of these previous studies (Clark et al., 2012; Julvez et al., 2021; van Kempen et al., 2010, 2012) but not with some others (Foraster et al., 2022; Lercher et al., 2016; Matheson et al., 2010; Stansfeld et al., 2005). Lercher et al. reported that higher residential exposure to road traffic and railway noise was related with worse memory in children around 9 years old (Lercher et al., 2016). In contrast, two other studies found an unexpected association between exposure to road traffic noise at schools and better memory in children aged 9–10 years (Matheson et al., 2010; Stansfeld et al., 2005). According to a recent study, children aged 7–10 who were exposed to higher road traffic noise levels at school had slower development in working memory (Foraster et al., 2022). But this association was not found for exposure to road traffic noise at participants' residential addresses. In addition, this study measured noise fluctuations at schools defined as the average number of noise peaks that stood out from background noise as well as the intermittency ratio of noise levels from isolated events to the overall noise level during the measurement period. They observed that exposure to higher number of noise peaks in the classroom, the school playground, and the school street, and to

Table 3
Fully adjusted associations of a 10 dB increase in prenatal and childhood outdoor exposure to residential road traffic noise and non-verbal and verbal intelligence, memory, and processing speed outcomes for the INMA-Sabadell cohort and the Generation R Study.

	Non-verbal intelligence		Verbal intelligence		Memory		Processing speed	
	Coef.	(95 % CI)	Coef.	(95 % CI)	Coef.	(95 % CI)	Coef.	(95 % CI)
Prenatal exposure								
INMA	0.15	−1.68; 1.98	−0.81	−2.59; 0.96	−1.08	−3.23; 1.07	0.16	−2.31; 2.63
Generation R	0.18	−0.24; 0.59	0.38	−0.05; 0.81	0.18	−1.03; 1.39	0.29	−0.32; 0.89
Overall	0.18	−0.22; 0.58	0.11	−0.86; 1.09	−0.13	−1.20; 0.93	0.28	−0.31; 0.87
Childhood exposure								
INMA	−0.18	−1.98; 1.62	−0.95	−2.70; 0.80	−1.18	−3.39; 1.03	0.09	−2.59; 2.76
Generation R	0.01	−0.44; 0.47	0.08	−0.39; 0.54	−0.82	−2.20; 0.55	0.48	−0.24; 1.19
Overall	−0.00	−0.44; 0.44	−0.08	−0.81; 0.65	−0.92	−2.08; 0.24	0.45	−0.22; 1.14

Abbreviations: Coef; coefficient; CI, confidence interval.
Coefficients and 95% confidence intervals by cohort were obtained by linear regression mixed models for non-verbal and verbal IQ and linear regression models for memory and processing speed outcomes. Models were adjusted for child sex, parental age, height, weight, body mass index, country of birth, education, social class, parity, smoking and alcohol during pregnancy, and family status. Overall coefficients and 95% confidence intervals were obtained by random-effects *meta*-analysis.

Table 4
Fully adjusted associations of a 10 dB increase in prenatal and childhood outdoor exposure to residential road traffic noise and attentional function outcomes for the INMA-Sabadell cohort and the Generation R Study.

	Commission errors		Omission errors		Visuomotor attention	
	IRR	(95 % CI)	IRR	(95 % CI)	Coef.	(95 % CI)
Prenatal exposure						
INMA	**0.88**	**0.81; 0.96**	**1.13**	**1.01; 1.28**	0.86	−1.57; 3.29
Generation R	0.96	0.77; 1.21	0.98	0.88; 1.08	1.01	−0.16; 2.18
Overall	NA	NA	NA	NA	0.98	−0.08; 2.04
Childhood exposure						
INMA	**0.85**	**0.78; 0.93**	1.13	0.99; 1.27	1.02	−1.60; 3.65
Generation R	0.95	0.75; 1.21	0.98	0.87; 1.10	0.17	−1.18; 1.51
Overall	NA	NA	NA	NA	0.35	−0.84; 1.54

Abbreviations Coef; coefficient; CI, confidence interval; IRR, incidence risk ratio; NA, Not Applicable.
Coefficients and 95% confidence intervals by cohort were obtained by negative binomial models for the attentional function and linear regression models for the visuomotor attention outcome. Models were adjusted for child sex, parental age, height, weight, body mass index, country of birth, education, social class, parity, smoking and alcohol during pregnancy, and family status. Overall coefficients and 95% confidence intervals were obtained by random-effects *meta*-analysis.
In bold, associations $p < 0.05$.

Table 5
Fully adjusted associations of a 10 dB increase in prenatal and childhood outdoor exposure to residential road traffic noise and motor function for the INMA-Sabadell cohort and the Generation R Study.

	Fine motor function		Gross motor function	
	Coef.	(95 % CI)	Coef.	(95 % CI)
Prenatal exposure				
INMA	0.17	−2.33; 2.67	0.28	−1.98; 2.53
Generation R	−0.24	−0.87; 0.39	−0.09	−0.47; 0.29
Overall	−0.22	−0.83; 0.39	−0.07	−0.64; 0.50
Childhood exposure				
INMA	−1.13	−3.78; 1.52	0.26	−2.06; 2.56
Generation R	0.46	−0.26; 1.18	0.04	−0.38; 0.47
Overall	0.20	−0.96; 1.35	0.05	−0.38; 0.47

Abbreviations Coef; coefficient; CI, confidence interval.
Coefficients and 95% confidence intervals by cohort were obtained by linear regression models. Models were adjusted for child sex, parental age, height, weight, body mass index, country of birth, education, social class, parity, smoking and alcohol during pregnancy, and family status. Overall coefficients and 95% confidence intervals were obtained by random-effects *meta*-analysis.

higher noise intermittency ratio in the classroom and the school playground were related to slower working memory development, while this association was not found in relation to indoor annual average noise levels in the classrooms. This novel finding can support the hypothesis that noise fluctuations might be more disruptive for children's neurodevelopment than average noise levels (Foraster et al., 2022). Unfortunately, we were not able to estimate noise fluctuations in our study. Future studies providing an improved assessment of noise exposure including measured and modelled noise events (Brown & De Coensel, 2018; Foraster et al., 2022) are warranted to investigate the potential effects of noise exposure on child's cognitive development.

Regarding attentional function, our null results were in line with several studies that did not find an association with road traffic noise exposure (Cohen et al., 1973; Julvez et al., 2021; Lercher et al., 2016; Stansfeld et al., 2005). However, two studies found that children attending schools with higher road traffic noise levels made more errors in the most difficult parts of the attention tests (van Kempen et al., 2010, 2012). Also, Foraster et al. reported that both outdoor and indoor exposures to road traffic noise at school, as well as higher noise fluctuations assessed as number of noise peaks and noise intermittency ratio, were associated with greater inattentiveness in children aged 7–10 years whereas home-outdoor noise exposure was not associated with attentional function (Foraster et al., 2022). Children and preadolescents spend most of the time at schools when road traffic noise levels are higher. Therefore, it could be possible that exposure to noise at school, instead of at home, may have more negative effects on concentration and learning processes.

The main strength of our study is the availability of data in children and preadolescents from two population-based birth cohorts from two different European countries. Another strength is the longitudinal nature of these cohort studies which allows us to assess the chronic exposure instead of the acute exposure to noise. It has been suggested that chronic noise exposure may have far more detrimental effects on cognitive function compared to acute noise exposure (Mac Domhnaill et al., 2021). Also, related to the noise exposure assessment, we considered the residential mobility accounting for the time that child spent at each address during the entire follow-up. We have also used multiple imputation and inverse probability weighting to reduce the potential selection bias (Spratt et al., 2010; Weuve et al., 2012). Furthermore, the assessment of repeated measurements for some of the cognitive outcomes using linear mixed models increased the statistical power of the analysis, allowing the correct modeling of the non-independence in the longitudinal data and accounting for the missing data (Harrison et al., 2018).

However, our study has some limitations that merit discussion. The main limitation of the study is that the estimation of individual noise levels for each participant was done using existing modeled noise maps. Personal noise measurements would be a more precise method to assess individual levels of exposure. However, in cohort studies with a large number of participants, the use of personal noise measurements is time-consuming and very expensive. Additionally, personal noise measurements are often carried out for a short period of time and do not reflect the long-term exposure as compared to noise models. Nevertheless, modeled exposures are more likely to be prone to misclassification. In the present study, noise levels corresponded to outdoor residential noise rather than indoor noise levels in the child's bedroom. Also, we were not able to include noise assessment at schools because this data was unfortunately not available. Thus, misclassification due to underestimation or overestimation of accurate noise exposure cannot be excluded in this study. Furthermore, we considered modeled average noise levels that did not account for noise fluctuations, while these fluctuations could be more disruptive for children's cognition than average noise levels (Foraster et al., 2022). Further studies including both indoor and school noise measurements, as well as noise fluctuations, are warranted since previous studies have shown that noise levels in these settings both assessed as continuous levels or as the recurrence of isolated loud noises might have a higher negative impact on children's cognitive function that outdoor levels. Another limitation is the possibility of the introduction of measurement error due to the lack of information on noise sensitivity (i.e., the physiological and psychological individual perception and the degree of reactivity to noise) or on the location and floor level of the child's bedroom, the type of residence insulation, or the quality and construction year of the building. Related to the outcome assessment, information bias might be introduced since we used different validated tests to assess cognitive outcomes at different ages and also between cohorts. However, we standardized all the cognitive scales to make them comparable between ages and study cohorts, and results were quite consistent across ages and study cohorts. Finally, we included a large number of outcomes which gave richness to the study but also implied a large number of statistical tests that needed to be corrected for multiple testing to avoid the occurrence of false positives. However, our study might not have had enough statistical power for so many tests and failed to detect a true association. Further studies including larger sample sizes to increase the statistical power are needed.

5. Conclusions

In conclusion, this study indicates that residential exposure to road traffic noise during pregnancy and childhood was not associated with cognitive and motor function outcomes in children and preadolescents. Future research including indoor noise measurements both at school and home environments, as well as noise events, should be contemplated to further explore the association. Furthermore, populations with higher prevalence of people exposed to other noise sources (i.e., railway, aircraft, or industrial) in school and residential settings should be considered in future studies in order to obtain a more comprehensive noise exposure assessment and compare the potential differential effects of each source of exposure in each setting on children's cognitive and motor function.

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CRediT authorship contribution statement

Laura Pérez-Crespo: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **Mónica López-Vicente:** Formal analysis, Writing – review & editing. **Antònia Valentín:** Methodology, Writing – review & editing. **Miguel Burgaleta:** Writing – review & editing. **Maria Foraster:** Writing – review & editing. **Henning Tiemeier:** Methodology, Funding acquisition, Writing – review & editing. **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 datasets generated and analyzed during the current study are not publicly available due to legal and ethical regulations, but may be made available upon request to the Directors of the INMA Project, Mònica Guxens (monica.guxens@isglobal.org), and of the Generation R Study, Vincent Jaddoe (v.jaddoe@erasmusmc.nl), in accordance with the local, national, and European Union regulations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.108414.

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