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The Relationship between $PM_{2.5}$, Greenness, and Road Noise Exposures and Children's Cognitive Performance in England: The Millennium Cohort Study

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Abstract: Research to date suggests that air pollution may affect children's cognitive development. This study followed 12,159 children in the Millennium Cohort Study in England for 17 years to assess the impacts of lifetime $PM_{2.5}$ exposure at home and school on cognitive performance while accounting for the inter-related environmental factors of greenness and road noise. Lifetime environmental exposures were measured at home from age 9 months and at school from age 5 years. The relationships between $PM_{2.5}$ and cognitive test performance at ages 3, 5, 7, 11, 14 and 17 years were investigated using multivariable linear regression models accounting for survey design and controlling for greenness, road noise, and other individual, family, school, and areal characteristics. The results suggest little evidence of observable associations between $PM_{2.5}$ and cognitive performance in England, with or without adjustment for greenness and road noise, at any age in the study population. These findings also apply to greenness and road noise. This is the first study to quantify the relationship between air pollution, greenspace, noise, and children's cognitive performance in a longitudinal cohort study in England.

Keywords: particulate matter; health and environmental air pollution impacts; greenspace; noise; cognitive performance; children

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1. Introduction

Exposure to air pollution, such as fine particulate matter of 2.5 µm or smaller in diameter ($PM_{2.5}$), has been linked to negative health outcomes across bodily systems [1]. Research indicates that $PM_{2.5}$, alongside other environmental determinants, specifically greenness and road noise, may influence human health independently and in conjunction with one another [2–4]. $PM_{2.5}$ and road noise share similar sources, primarily motorised vehicles, while the amount of vegetation in an area (greenness) can mitigate exposure to such harmful pollutants [5,6]. Evidence suggests that some vulnerable groups, importantly children, may experience cognitive changes to the developing brain as a result of prolonged exposure to $PM_{2.5}$, greenness, and road noise [7–9]. Most research in the area has considered the effects of a single environmental exposure on age-appropriate cognitive tests or educational attainment outcomes at a specified time-point during childhood or adolescence [7]. Nevertheless, some studies recognise the importance of examining the effects of multiple exposures due to their interrelated nature and investigate diverse cognitive outcomes throughout development in order to explore nuances in the associations [2,3,10].

Research investigating the relationships between air pollutants and children's cognition most often focus on impacts in early childhood. A study of prenatal exposure found that one microgram per cubic metre ($\mu g/m^3$) increases in $PM_{2.5}$ were related to −0.4 decreases in language function among 740 toddlers in Mexico City [11]. When examining lifetime exposure, including during pregnancy, research has shown that a 2 μg/m^3 increase in $PM_{2.5}$ may be associated with 3.6 lower intelligence quotient (IQ) scores among a cohort of 2000 children ages 4–6 years [12]. Other studies of prenatal and lifetime exposure to particulate matter of varying dimensions in the United States, Spain, and Iran suggest that the negative effects on children's cognition may only be present among boys or may be modified by socioeconomic factors and urbanicity [13–16]. These analyses do not account for school exposure or school characteristics; however, Spanish and Chinese research that focuses on children's short-term, one-year $PM_{2.5}$ exposure demonstrates detrimental impacts on working memory and executive function from residential but not school exposure, as well as exposure while commuting to school on foot [17–19]. Mechanistic investigations that attempt to explain the pathway from air pollution exposure to cognitive effects indicate that $PM_{2.5}$ is inhaled into the body, with the potential to enter the bloodstream, and may cause neuroinflammation and oxidative stress, leading to changes in brain structure and function [1,20–22].

An evidence base also exists for the positive impact of greenness exposure on children's cognitive development. Cross-sectional evidence from a cohort of Canadian adolescents demonstrates a 0.1 increase in attentiveness scores per interquartile range (IQR) increase in residential greenness within one kilometre (km) [23]. Other cross-sectional research in younger age groups in the United Kingdom and Belgium also indicates improvements in memory related to residential greenness [24,25]. When examining lifetime exposure in early childhood, a study found a 2.6% increase in memory in mid-childhood, after accounting for early cognition [26]. Further longitudinal research suggests that improved attention among 1000 children from ages 4–7 years old may be associated with lifetime residential greenness since birth [27]; however, other evidence that included more robust measures of family- and neighbourhood-level socioeconomic status indicated no measurable relationship between IQ and greenness throughout childhood and adolescence in a cohort of 1658 Britons after controlling for socioeconomic factors [28]. Studies that examined greenness exposure at school in the UK and Belgium have also found positive associations with cognition in adolescence [29,30]. A greenness–cognition review paper suggested that the protective effects of greenness exposure may be due to reduced levels of air pollution and noise, as well as the promotion of physical activity and other healthy behaviours [31].

Evidence of the effects of noise on children's cognition predominantly focuses on school-level exposure. A cross-national European study of 9–10-year-olds found that one decibel (dB) increases in chronic aircraft noise at school was related to -0.01 decreases in reading and memory scores, whereas 1 dB increases in road traffic noise were unexpectedly associated with 0.01 to 0.05 increases in memory scores [32]. Despite relatively low levels of aircraft noise around an airport in Germany, researchers also demonstrated that a 20 dB increase in aircraft noise was related to decreases in reading scores equivalent to a two-month learning delay at ages 7–8 years [33]. An interrupted time-series study before and after the closure of an airport in Thailand showed that decreases in noise exposure were associated with improved long-term memory scores among a cohort of 284 primary school children [34]. Recent research examining noise exposure at home and school provides mixed evidence; a Brazilian study found a longitudinal association between 24 h road noise and decreased cognition among 3385 young children, whereas researchers in Serbia only observed adverse impacts among boys in their sample of 7–11-year-olds [35,36]. Evidence in this area indicates that noise exposure may disrupt cognitive processes, such as sleep and learning, and increase physiological stress, resulting in impaired cognition [37].

Several studies examine more than one environmental determinant among air pollution, greenness, and noise in relation to cognition. A study of 1312 young Chinese children's residential greenness exposure, measured every 500 metres (m) (spatial resolution), found that although greenness was related to improved mental development scores at age 2 years, 13–28% of the association could be explained by decreases in traffic-related air pollution (TRAP) through a mediation analysis [38]. Nonetheless, another study found that up to 65% of the relationship between cognition and greenness measured at home and school at a higher 5 m resolution may be accounted for by TRAP among 2600 Spanish 7–10-year-olds [39]. A much larger birth cohort of over 27,000 Canadian children further indicates that lifetime exposure to greenness may be related to improved early development, and that 97% of the improvement was mediated by reductions in $PM_{2.5}$ and road noise [40]. Research investigating the environment–cognition link using other methods produce contrasting results. Two Spanish studies of 7–11-year-old children found that greenness and road noise were independently related to attention and memory, even when controlling for air pollution [41,42]. In parallel, research examining air pollution and noise demonstrated that both exposures were related to poorer cognition in 9–10-year-olds after mutual adjustment [2,43]. Given their interrelation, it may be important to consider greenness and noise exposure when investigating the impacts of $PM_{2.5}$ on children's cognition.

Although some research has quantified the relationships between major environmental factors and children's cognition, it remains an emerging research area. The evidence base lacks longitudinal studies that examine a range of cognitive assessments throughout development alongside a comprehensive set of relevant individual-, family-, school-, and area-level covariates [7,10]. The present study investigates the associations between $PM_{2.5}$ and children's cognitive performance from ages 3 to 17 years, while considering greenness and road noise, in England, in the Millennium Cohort Study (MCS). Previous research with the MCS has demonstrated some evidence of associations between air pollution, greenspace, and cognitive scores, respectively, but these studies only examined neighbourhood-level exposure and cognition during early childhood [25,44–46]. This large cohort study builds upon the evidence by assessing postcode-level $PM_{2.5}$, greenness, and road noise exposure at home and school in the same model, in relation to cognition in childhood and adolescence, while controlling for an extensive series of confounding factors. The results aim to provide further insight into the increasingly salient environment–cognition research area [47].

2. Materials and Methods

2.1. Study Population

The Millennium Cohort Study (MCS) is a nationally representative longitudinal study of 19,517 children born between September 2000 and January 2002, followed from age 9 months in the United Kingdom (UK) [48]. A stratified sampling design by country and electoral ward type was used that oversampled families with socio-economic disadvantages, minority ethnic groups, and populations in Scotland, Wales, and Northern Ireland [49]. The MCS has collected demographic, developmental, and economic information on the cohort members and their families through interviews and questionnaires across seven sweeps at ages 9 months (2001–2003), as well as at 3 (2003–2005), 5 (2006), 7 (2008), 11 (2012–2013), 14 (2015–2016), and 17 (2018–2019) years of age. Further information on the data and their collection is detailed by the University College London's (UCL) Centre for Longitudinal Studies.

This study focuses on a subset of children in England from the MCS with productive surveys (n = 12,223) who consented to data linkage with their school information (80.25%). Children's residential postcodes were tracked from age 9 months; school-unique reference numbers (URN) were recorded annually from the start of formal schooling at age 5 years. A history of environmental exposures reflecting moves in residences and schools and other characteristics related to cognitive performance detailed below were generated annually for each child over 17 years until the latest MCS sweep. Only children with complete information on residential and school exposures, cognitive performance, and pre-defined covariates at each MCS sweep were included; these factors, alongside subject attrition, explain why a smaller number of MCS children were examined at each progressive sweep. The resulting analytic samples consisted of 8312 children at age 3 years (MCS2), 5172 children at age 5 years (MCS3), 5171 children at age 7 years (MCS4), 3881 children at age 11 years (MCS5), 2661 children at age 14 years (MCS6) and 2261 children at age 17 years (MCS7).

Ethics approval was gained from the London School of Hygiene and Tropical Medicine Ethics Committee, reference #26559. Data access was granted by the Centre for Longitudinal

Studies at UCL; all data linkage and analyses were completed in the UCL Data Safe Haven (DSH), in line with data protection protocols.

2.2. Cognitive Outcomes

Children completed a variety of age-appropriate cognitive tests at each sweep, from MCS2 through MCS7. The British Abilities Scales II (BAS II), an individually administered series of tests to assess cognitive ability, were used in most age groups, alongside several other measures. At age 3 years (MCS2), the BAS II Naming Vocabulary—assessing expressive language skills and vocabulary using long-term memory—and the Bracken School Readiness Assessment-Revised (BSRA-R)—measuring children's understanding of basic concepts in preparation for school—were administered. At age 5 years (MCS3), Naming Vocabulary, Pattern Construction—assessing spatial problem-solving and hand–eye coordination using visual processing—and Picture Similarities—measuring inductive reasoning—from the BAS II were conducted. At age 7 years (MCS4), BAS II Word Reading—involving recognition and oral reading of single words without contextual clues—and Pattern Construction were used alongside the National Foundation for Educational Research (NFER) Progress in Maths (adapted)—a measure of mathematical ability covering numbers, shapes, measurement, and data handling. At age 11 years (MCS5), the BAS II Verbal Similarities—assessing verbal reasoning, vocabulary, and language skills—was employed. At age 14 years (MCS6), the Applied Psychology Unit (APU) Vocabulary Test—measuring vocabulary knowledge—was used. At age 17 years (MCS7), the Number Analogies short version of the Quantitative Reasoning Battery—determining reasoning ability with numbers—was administered. Performance on all cognitive tests was standardised into Z-scores using the raw scores of each measure. Higher scores indicate increased cognitive ability across all tests. A figure demonstrating the cognitive tests completed at each age by children in the MCS can be found in Appendix A.

2.3. Exposure Assessments

2.3.1. Fine Particles ($PM_{2.5}$)

The Department for Environment, Food and Rural Affairs (Defra) modelled background pollution data provided the maps of annual average $PM_{2.5}$ levels across England that were used in this study from 2002 to 2018, measured in micrograms per cubic metre (μg/m^3) at a 1 × 1 kilometre (km) resolution [50]. Contributions from various point and areal emission sources detailed in the National Atmospheric Emissions Inventory (NAEI) in industrial, domestic, road traffic, and rural areas as well as various other sources were combined to determine background $PM_{2.5}$ concentrations. Additional sources of background $PM_{2.5}$ concentrations, such as secondary (in)organic aerosols, regional primary particles, regional calcium and iron-rich dusts from re-suspension, iron-rich dusts from re-suspension due to vehicle activity, sea salt and residuals, were also considered. Furthermore, roadside increment concentrations from urban major road census points (A roads and motorways) were also computed. In this way, thorough roadside assessments were made while keeping the link with Automatic Urban and Rural Network (AURN) measurement data to adjust this component of the model. A more specific modelling methodology is detailed elsewhere [51]. The closest value on the $PM_{2.5}$ grid to the centroid of residential and school full-postcode boundaries was estimated for every year in the Quantum Geographic Information System (QGIS) 3.16.8 'Hannover' to capture annual exposure to $PM_{2.5}$ at home and school. From 2002 until starting school in 2006, children's exposure was defined solely based on their home residence. In order to reflect both residential and school exposures to $PM_{2.5}$ from 2006 onwards, an occupancy time-weighted combined exposure measure was created for each year from 2006 to 2018, accounting for 17 h of exposure at home and 7 h at school. In our statistical models, lifetime average exposure to $PM_{2.5}$ was defined, encompassing the follow-up period from 2002 until each sweep when the cognitive assessments took place.

2.3.2. Greenness

The Copernicus Global Land Service, the Earth Observation programme of the European Commission, provided the greenness measure used in this study, referred to as the Normalised Difference Vegetation Index (NDVI), a remote sensing technique used to quantify the health and density of vegetation [52]. The NDVI is measured at a 1 km resolution by a PROBA-VEGETATION sensor that computes Red and Nir reflectance values using the 10-daily Top of the Canopy reflectance (copyright BELSPO and distribution by VITO NV) [53]. The values of NDVI vary from −0.08, representing burnt areas, to 0.92, representing the greenest areas; any values outside of this scale represent missing values where data were not collected. Using QGIS, the annual average NDVI value was measured at each residential (from 2002 to 2018) and school (from 2006 to 2018) postcode boundary centroid. In this sample, there were no NDVI values less than zero. The lifetime average exposure model for $PM_{2.5}$ detailed above, including time-weighted combined exposure at home and school, was also applied to greenness exposure.

2.3.3. Road Noise

Through personal communication with Defra's Noise Team, Strategic Noise Mapping of road noise data from 2012, collected in 2010 [54], and 2017, collected in 2015–2016, were procured [55]. A full description of the methodology used in Defra's Strategic Road Mapping is detailed elsewhere [56]. Briefly, under the Environmental Noise Directive (rounds 2 and 3), road noise was measured in decibels (dB) on a 10 m grid across 26,000 km of major roads and 65 agglomerations at 4 metres (m) above local ground level by Defra. As a means to consider all noise sources affecting noise levels within the calculation area, a 3 km buffer for roads and a 1 km buffer for agglomerations were included, covering an area of approximately 77,000 km^2 of England. Motorways and A roads within agglomerations and roads with more than 3 million vehicle movements per year are considered major roads.

In QGIS, annual average road noise levels were estimated for each child for the evening 7–11 p.m. ($L_{evening}$) and nighttime 11 p.m.–7 a.m. (L_{night}) at the centroid of the home postcode boundary, and for the daytime 7 a.m.–7 p.m. (L_{day}) at the centroid of the school postcode boundary. Given that the L_{night} measure contained a high number of missing values and that $L_{evening}$ and L_{night} measures were highly correlated ($r = 0.98$) in our sample, $L_{evening}$ was used to capture children's residential road noise exposure. In order to create yearly noise exposure data, road noise data collected in 2010 were applied to 2002–2012, and the corresponding data collected in 2015–16 were applied to 2013–2018. In this sample, values where road noise is missing indicate postcodes that are not in proximity to major roads or where Defra declared the measurements inaccurate due to being below 35 dB. For the purpose of preserving the whole sample, a dummy variable was used to include children with missing road noise exposure data (26.60%) in the analyses. The lifetime average exposure model for $PM_{2.5}$ stated previously, including the time-weighted combined exposure at home and school, was also applied to road noise exposure.

2.4. Other Major Risk Factors

Other major risk factors at individual, family, school, and area levels from the MCS were determined based on research in the area [46,57]. The individual-level covariates included, as follows: relative age in months; gender (male; female); ethnicity (White; Mixed; Indian; Pakistani and Bangladeshi; Black; other); and low birthweight (normal (≥2.5 kg (kg)); low (<2.5 kg); unknown). The family-level characteristics included, as follows: the language spoken in the household (English only; mostly English or half English; mostly others, others only or unknown); number of siblings in the household (none; one; two; three or more and unknown); maternal age in years at child's birth; whether breastfeeding was ever tried (yes; no; unknown); household income measured by the Organisation for Economic Co-operation and Development (OECD) income-weighted quintiles (lowest; second; third; fourth; highest); and parental education indicated by the main respondents' highest National Vocational Qualification (NVQ level 1; NVQ level 2;

NVQ level 3; NVQ level 4; NVQ level 5; other qualification; none/unknown) and partner (NVQ level 1; NVQ level 2; NVQ level 3; NVQ level 4; NVQ level 5; other qualification; none; unknown). An NVQ is a UK-based work qualification consisting of five levels that assesses the skills and knowledge related to particular jobs across a range of sectors. The school-level factors included, as follows: the school gender (male, female or mixed); pupils with ethnic backgrounds of White (%), Black (%), South Asian (%), Chinese (%) or others (%); pupils with English as an additional language (%); pupils eligible for free school meals (FSM) (%); the ratio of teachers to pupils; the ratio of teaching assistants (TA) to teachers; and institution type (Academies, Community Schools, Voluntary Schools, Foundation Schools, Technology Colleges, Special Schools, Free Schools and Studio Schools). The area-level characteristics measured at residential postcodes included, as follows: the Region Code; quintiles of population density of all Output Areas (OA); and deciles of the Income Deprivation Affecting Children Index (IDACI)—the proportion of all children aged 0 to 15 living in income deprived families—of all Lower Super Output Areas (LSOA) [58].

2.5. Statistical Analyses

2.5.1. Study Population and Environmental Exposures

Initial descriptive statistics and correlations among environmental exposures, cognitive outcomes, and covariates at each MCS sweep were generated to examine any associations between the variables included in the analyses.

2.5.2. Impacts on Cognitive Performance

Multivariable linear regression models of lifetime $PM_{2.5}$ exposure on cognitive test scores from each sweep at ages 3, 5, 7, 11, 14 and 17 years were performed, accounting for survey design and subject attrition using Stata svyset command [59]. Every multi-environmental exposure model included, as follows: all other environmental (greenness and road noise); individual (age, gender, ethnicity and birthweight); family (language, number of siblings, maternal age at child's birth, breastfeeding, household income and parental education); school fixed effects (school gender, ethnicity%, language%, free school meal eligibility%, teacher–student ratio, teaching assistant–teacher ratio and institution type); and areal (region, population density quintiles and IDACI deciles) factors. Single environmental exposure models unadjusted for related environmental characteristics—$PM_{2.5}$, greenness, and road noise, respectively—were investigated for comparability. The statistical models assess the contribution of lifetime environmental exposures and key covariates to cognitive performance throughout development, and consider the sampling, stratification, attrition, and survey design of the MCS through adjustment of the standard errors. All results of $PM_{2.5}$, greenness and road noise exposures are expressed as the change in standardised scores for an interquartile range (IQR) increase in each average environmental measure. Analyses were performed in Stata version 17 (example Stata code provided in Appendix B).

2.5.3. Impacts on Cognitive Trajectory

An additional analysis was explored to determine children's cognitive trajectory at ages 5, 7, 11, 14 and 17 years by using average time-weighted exposures since the last sweep while controlling for performance on the cognitive tests at the previous MCS measurement; all other features of the multivariable linear regression models stayed constant. Furthermore, a number of sensitivity analyses were conducted using models identical to those in the main analyses except for, as follows: (1) examining environmental exposures from one year prior to each educational measurement (one-year lag); (2) restricting the analyses to pupils with available road noise data that reside and attend schools near major roads (n = 8972); and (3) excluding school characteristic covariates.

3. Results

3.1. Study Population and Environmental Exposures

Following data linkage between lifetime environmental exposures, cognitive outcomes and related covariates, 8312 children were examined at age 3 years (MCS2), 5172 children at age 5 years (MCS3), 5171 children at age 7 years (MCS4), 3881 children at age 11 years (MCS5), 2661 children at age 14 years (MCS6) and 2261 children at age 17 years (MCS7). Characteristics of the analytic samples in lifetime exposure models, including individual-, family-, school-, and area-level factors, are presented in Table 1. Among the sample of children, White ethnicity is the most common (72.4% at MCS4) as well as having a normal birthweight (87.7% at MCS4), only speaking the English language at home (79.4% at MCS4), having one other sibling (44.3% at MCS4), and being breastfed in early life (70.6% at MCS4). Most parents of children in the sample possess an NVQ level 2, covering complex, work-based duties (28.5% and 22.8% at MCS4 among main and partner respondents, respectively), or NVQ level 4, representing specialist-level roles (26.6% and 23.4% at MCS4 among main and partner respondents, respectively). Once children start school, most attend mixed-gender (99.9% in MCS4) community schools (70.6% at MCS4). Individual, family, school, and areal characteristics of the analytic samples are comparable across study sweeps.

Table 1. Characteristics of the analytic sample of MCS children at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) linked to lifetime environmental exposures.

		MCS2 Age 3 (n = 8312)	**MCS3 Age 5 (n = 5172)**	**MCS4 Age 7 (n = 5171)**	**MCS5 Age 11 (n = 3881)**	**MCS6 Age 14 (n = 2661)**	**MCS7 Age 17 (n = 2261)**
Child-level							
Relative age, months	Median (IQR)	6 (6)	6 (6)	6 (6)	5 (6)	5 (6)	5 (5)
Gender, n (%)	Male	4114 (49.5)	2615 (50.6)	2596 (50.2)	1934 (49.8)	1307 (49.1)	1068 (47.2)
	Female	4198 (50.5)	2557 (49.4)	2575 (49.8)	1947 (50.2)	1354 (50.9)	1193 (52.8)
Ethnicity, n (%)	White	6571 (79.1)	3816 (73.8)	3742 (72.4)	2695 (69.4)	1791 (67.3)	1477 (65.3)
	Mixed	319 (3.8)	198 (3.8)	207 (4)	171 (4.4)	184 (6.9)	161 (7.1)
	Indian	322 (3.9)	243 (4.7)	252 (4.9)	213 (5.5)	155 (5.8)	145 (6.4)
	Pakistani and Bangladeshi	647 (7.8)	509 (9.8)	549 (10.6)	473 (12.2)	267 (10)	233 (10.3)
	Black	336 (4)	283 (5.5)	295 (5.7)	230 (5.9)	163 (6.1)	150 (6.6)
	Other	117 (1.4)	123 (2.4)	126 (2.4)	99 (2.6)	101 (3.8)	95 (4.2)
Birthweight, n (%)	Normal	7307 (87.9)	4534 (87.7)	4533 (87.7)	3393 (87.4)	2342 (88)	2000 (88.5)
	Low	601 (7.2)	399 (7.7)	396 (7.7)	309 (8)	201 (7.6)	161 (7.1)
	Unknown	404 (4.9)	239 (4.6)	242 (4.7)	179 (4.6)	118 (4.4)	100 (4.4)
Family-level							
Language, n (%)	English only	6905 (83.1)	4142 (80.1)	4108 (79.4)	3076 (79.3)	2153 (80.9)	1789 (79.1)
	Mostly English	1165 (14)	665 (12.9)	719 (13.9)	545 (14)	347 (13)	332 (14.7)
	Other/unknown	242 (2.9)	365 (7.1)	344 (6.7)	260 (6.7)	161 (6.1)	140 (6.2)
Number of siblings, n (%)	0	2081 (25)	821 (15.9)	604 (11.7)	441 (11.4)	357 (13.4)	438 (19.4)
	1	3842 (46.2)	2397 (46.4)	2288 (44.3)	1635 (42.1)	1172 (44)	1003 (44.4)
	2	1549 (18.6)	1258 (24.3)	1435 (27.8)	1065 (27.4)	689 (25.9)	521 (23)
	3+/unknown	840 (10.1)	696 (13.5)	844 (16.3)	740 (19.1)	443 (16.7)	299 (13.2)
Maternal age	Median (IQR)	31 (8)	31 (8)	31 (8)	32 (9)	32 (8)	32 (8)
Breastfeeding, n (%)	Yes	5854 (70.4)	3658 (70.7)	3651 (70.6)	2796 (72)	1986 (74.6)	1740 (77)
	No	2059 (24.8)	1279 (24.7)	1283 (24.8)	911 (23.5)	561 (21.1)	426 (18.8)
	Unknown	399 (4.8)	235 (4.5)	237 (4.6)	174 (4.5)	114 (4.3)	95 (4.2)
Household income, n (%)	1 (lowest)	1735 (20.9)	1196 (23.1)	1154 (22.3)	811 (20.9)	463 (17.4)	350 (15.5)
	2	1634 (19.7)	1067 (20.6)	1001 (19.4)	782 (20.2)	421 (15.8)	346 (15.3)
	3	1626 (19.6)	1019 (19.7)	1045 (20.2)	735 (18.9)	480 (18)	410 (18.1)
	4	1600 (19.3)	973 (18.8)	1002 (19.4)	784 (20.2)	621 (23.3)	541 (23.9)
	5 (highest)	1717 (20.7)	917 (17.7)	969 (18.7)	769 (19.8)	676 (25.4)	614 (27.2)

Table 1. *Cont.*

		MCS2 Age 3 (n = 8312)	MCS3 Age 5 (n = 5172)	MCS4 Age 7 (n = 5171)	MCS5 Age 11 (n = 3881)	MCS6 Age 14 (n = 2661)	MCS7 Age 17 (n = 2261)
Main parent's education, n (%)	NVQ level 1	718 (8.6)	422 (8.2)	402 (7.8)	267 (6.9)	141 (5.3)	113 (5)
	NVQ level 2	2390 (28.8)	1521 (29.4)	1474 (28.5)	984 (25.4)	588 (22.1)	469 (20.7)
	NVQ level 3	1166 (14)	731 (14.1)	761 (14.7)	587 (15.1)	362 (13.6)	323 (14.3)
	NVQ level 4	2399 (28.9)	1372 (26.5)	1377 (26.6)	1115 (28.7)	887 (33.3)	788 (34.9)
	NVQ level 5	328 (4)	173 (3.3)	256 (5)	290 (7.5)	288 (10.8)	262 (11.6)
	Other	258 (3.1)	189 (3.7)	189 (3.7)	157 (4.1)	99 (3.7)	83 (3.7)
	None/unknown	1053 (12.7)	764 (14.8)	712 (13.8)	481 (12.4)	296 (11.1)	223 (9.9)
Partner parent's education, n (%)	NVQ level 1	535 (6.4)	339 (6.6)	327 (6.3)	236 (6.1)	133 (5)	104 (4.6)
	NVQ level 2	1897 (22.8)	1206 (23.3)	1179 (22.8)	880 (22.7)	538 (20.2)	436 (19.3)
	NVQ level 3	1019 (12.3)	631 (12.2)	632 (12.2)	471 (12.1)	347 (13)	296 (13.1)
	NVQ level 4	2132 (25.7)	1231 (23.8)	1212 (23.4)	902 (23.2)	694 (26.1)	638 (28.2)
	NVQ level 5	460 (5.5)	269 (5.2)	326 (6.3)	324 (8.4)	274 (10.3)	258 (11.4)
	Other	321 (3.9)	239 (4.6)	247 (4.8)	202 (5.2)	124 (4.7)	99 (4.4)
	None	897 (10.8)	664 (12.8)	636 (12.3)	439 (11.3)	260 (9.8)	220 (9.7)
	Unknown	1051 (12.6)	593 (11.5)	612 (11.8)	427 (11)	291 (10.9)	210 (9.3)
School-level							
Gender, n (%)	Male			3 (0.1)	3 (0.1)	482 (1.4)	101 (4.5)
	Female					711 (2.1)	202 (8.9)
	Mixed			5168 (99.9)	3878 (99.9)	32,809 (96.5)	1958 (86.6)
Ethnicity %, median (IQR)	White			63.6 (42.4)	64.3 (48.2)	80.4 (49.9)	78 (53.3)
	Black			0.6 (3.6)	0.6 (4.9)	1.4 (7.8)	2.2 (8.6)
	South Asian			1.7 (9.3)	2.4 (14.1)	3.4 (18.7)	4.1 (17.6)
	Chinese			<0.1 (0.4)	<0.1 (<0.1)	0.2 (0.4)	0.3 (0.4)
	Other			2.9 (3.9)	3.6 (5.2)	5 (3)	6.1 (6.8)
Non-English language %	Median (IQR)			6.2 (32.3)	10.1 (39.9)	10.6 (31.3)	10.9 (33.1)
FSM eligible pupils %	Median (IQR)			12.7 (20.5)	16.9 (19.1)	12 (15.2)	9.8 (11)
Teacher–pupil ratio	Median (IQR)			22.2 (3.7)	21.1 (3.8)	15 (2.5)	16.2 (2.6)
TA–teacher ratio	Median (IQR)			0.7 (0.5)	0.7 (0.4)	0.2 (0.1)	0.2 (0.2)
Institution type, n (%)	Academy			3 (0.1)	9 (0.2)	1508 (56.7)	1317 (58.3)
	Community			3652 (70.6)	2597 (66.9)	615 (23.1)	488 (21.6)
	Voluntary			1418 (27.4)	1059 (27.3)	335 (12.6)	287 (12.7)
	Foundation			92 (1.8)	198 (5.1)	164 (6.2)	133 (5.9)
	Special school			6 (0.1)	18 (0.5)	17 (0.6)	
	PRU/alternative					3 (0.1)	
	Tech College						13 (0.6)
	Free and Studio					19 (0.7)	23 (1)
Area-level							
Region, n (%)	North East	403 (4.9)	211 (4.1)	210 (4.1)	129 (3.3)	66 (2.5)	50 (2.2)
	North West	1111 (13.4)	732 (14.2)	736 (14.2)	525 (13.5)	443 (16.7)	363 (16.1)
	Yorkshire and the Humber	983 (11.8)	646 (12.5)	664 (12.8)	509 (13.1)	256 (9.6)	199 (8.8)
	East Midlands	722 (8.7)	420 (8.1)	417 (8.1)	300 (7.7)	164 (6.2)	130 (5.8)
	West Midlands	916 (11)	711 (13.8)	735 (14.2)	518 (13.4)	364 (13.7)	285 (12.6)
	East of England	826 (9.9)	257 (5)	254 (4.9)	200 (5.2)	107 (4)	104 (4.6)
	London	1246 (15)	1023 (19.8)	1001 (19.4)	807 (20.8)	595 (22.4)	555 (24.6)
	South East	1381 (16.6)	881 (17)	886 (17.1)	717 (18.5)	521 (19.6)	451 (20)
	South West	724 (8.7)	291 (5.6)	268 (5.2)	176 (4.5)	145 (5.5)	124 (5.5)
Population density quintiles, n (%)	1 (lowest)	1655 (19.9)	722 (14)	734 (14.2)	520 (13.4)	405 (15.2)	348 (15.4)
	2	1763 (21.2)	1048 (20.3)	1068 (20.7)	776 (20)	546 (20.5)	434 (19.2)
	3	1753 (21.1)	1137 (22)	1132 (21.9)	878 (22.6)	582 (21.9)	504 (22.3)
	4	1699 (20.4)	1189 (23)	1174 (22.7)	896 (23.1)	588 (22.1)	486 (21.5)
	5 (highest)	1442 (17.4)	1076 (20.8)	1063 (20.6)	811 (20.9)	540 (20.3)	489 (21.6)

Table 1. *Cont.*

		MCS2 Age 3 (n = 8312)	MCS3 Age 5 (n = 5172)	MCS4 Age 7 (n = 5171)	MCS5 Age 11 (n = 3881)	MCS6 Age 14 (n = 2661)	MCS7 Age 17 (n = 2261)
IDACI deciles, n (%)	1 (lowest)	852 (10.3)	654 (12.7)	573 (11.1)	286 (7.4)	174 (6.5)	141 (6.2)
	2	782 (9.4)	496 (9.6)	591 (11.4)	407 (10.5)	236 (8.9)	186 (8.2)
	3	784 (9.4)	539 (10.4)	549 (10.6)	384 (9.9)	251 (9.4)	212 (9.4)
	4	800 (9.6)	530 (10.3)	545 (10.5)	448 (11.5)	260 (9.8)	192 (8.5)
	5	922 (11.1)	557 (10.8)	500 (9.7)	425 (11)	279 (10.5)	233 (10.3)
	6	782 (9.4)	470 (9.1)	522 (10.1)	444 (11.4)	297 (11.2)	271 (12)
	7	859 (10.3)	528 (10.2)	517 (10)	435 (11.2)	293 (11)	257 (11.4)
	8	862 (10.4)	517 (10)	462 (8.9)	327 (8.4)	266 (10)	238 (10.5)
	9	842 (10.1)	401 (7.8)	470 (9.1)	334 (8.6)	300 (11.3)	268 (11.9)
	10 (highest)	827 (10)	480 (9.3)	442 (8.6)	391 (10.1)	305 (11.5)	263 (11.6)

N, unweighted number; IQR, interquartile range; %, weighted percentage; FSM, free school meal; TA, teaching assistants; IDACI, Income Deprivation Affecting Children Index.

Table 2 provides lifetime, one-year lag and trajectory average exposure estimates of $PM_{2.5}$, greenness, and road noise at each MCS sweep of the analytic sample. By age 7 years (MCS4), children are exposed to the environmental factors considered in this study at both home and school. In the lifetime exposure model, children at age 7 years (MCS4), for example, were exposed to on average 12.51 $\mu g/m^3$ of $PM_{2.5}$, greenness levels of 0.47 (NDVI), and 43.79 dB of road noise in this sample (Table 2). In Appendix C Table A1, a correlation matrix of sample exposure estimates is presented at age 7 years (MCS4). There is a strong correlation ($r > 0.92$ at MCS4) among lifetime, one-year lag, and trajectory environmental exposures. A moderate, negative correlation ($r < -0.47$ at MCS4) was found between greenness and $PM_{2.5}$ in this sample. For road noise, a very weak positive correlation ($r > 0.11$ at MCS4) was observed with $PM_{2.5}$ and a very weak negative correlation ($r < -0.1$ at MCS4) was observed with greenness. Exposure levels and associations among exposures in other sweeps are generally similar to those at age 7 years (MCS4) (Table 2 and Appendix C, Table A1).

Table 2. Summary of lifetime, one-year lag and trajectory average $PM_{2.5}$, greenness, and road noise exposures of the study sample.

		MCS2 Age 3 (n = 8312)	MCS3 Age 5 (n = 5172)	MCS4 Age 7 (n = 5171)	MCS5 Age 11 (n = 3881)	MCS6 Age 14 (n = 2661)	MCS7 Age 17 (n = 2261)
N of children	Lifetime	8312	5172	5171	3881	2661	2261
	1-year lag	8455	9673	7792	5859	5702	4797
	Trajectory		7598	7792	5710	5413	4580
$PM_{2.5}$, $\mu g/m^3$, Median (IQR)	Lifetime	13.18 (2.34)	13.07 (2.46)	12.51 (2.47)	12.36 (2.29)	11.99 (2.22)	11.75 (2.38)
	1-year lag	15.2 (2.66)	12.54 (2.8)	10.49 (2.65)	12.25 (2.31)	11.16 (1.91)	9.56 (2.83)
	Trajectory		12.24 (2.6)	10.76 (2.64)	11.64 (2.11)	10.7 (1.79)	9.87 (1.45)
Greenness, NDVI, Median (IQR)	Lifetime	0.47 (0.11)	0.47 (0.12)	0.47 (0.11)	0.47 (0.11)	0.48 (0.12)	0.48 (0.11)
	1-year lag	0.46 (0.11)	0.49 (0.13)	0.5 (0.11)	0.49 (0.11)	0.52 (0.11)	0.54 (0.1)
	Trajectory		0.5 (0.12)	0.5 (0.11)	0.49 (0.11)	0.51 (0.11)	0.53 (0.1)
Road noise, dB, Median (IQR)	Lifetime	43.28 (6.74)	43.5 (6.35)	43.79 (6.02)	44.08 (5.53)	44.24 (5.67)	44.36 (5.53)
	1-year lag	43.2 (6.92)	43.34 (6.76)	44.12 (6.13)	44.12 (5.96)	44.37 (6.18)	44.42 (6.29)
	Trajectory		43.61 (6.43)	44.19 (6.05)	44.15 (5.85)	44.4 (6.15)	44.41 (6.24)

N, unweighted number; IQR, interquartile range.

3.2. Impacts on Cognitive Performance

The estimated changes in standardised cognitive test scores for an IQR increase in lifetime and trajectory $PM_{2.5}$ (Figure 1), greenness (Figure 2) and road noise (Figure 3) exposures at each sweep in single environmental exposure, multi-environmental exposure and trajectory models are presented in Figures 1–3. Coefficients for each environmental exposure across sweeps and models are indicated in Appendix C, Table A2.

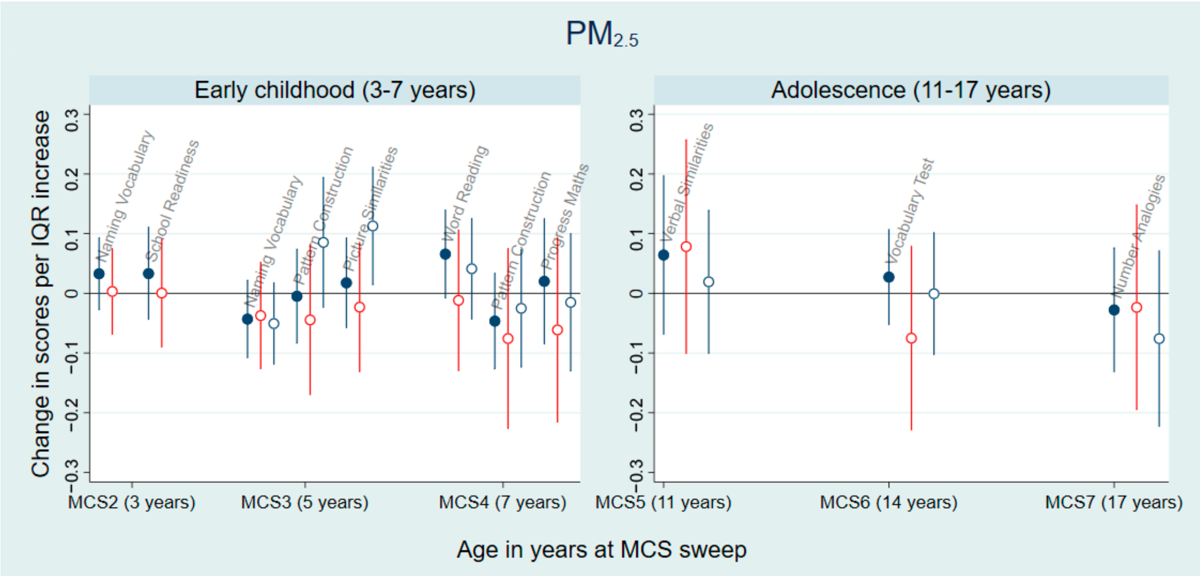

Figure 1. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per interquartile range (IQR) increase in lifetime and trajectory $PM_{2.5}$ exposure (IQR for MCS2 2.49, MCS3 2.54, MCS4 2.54, MCS5 2.24, MCS6 2.08 and MCS7 2.14 in $\mu g/m^3$). Navy filled circles and lines represent point estimates and 95% confidence intervals from single environmental exposure models, open red circles and lines represent those from multi-environmental exposure models, and navy open circles and lines represent those from trajectory models (IQR for MCS3 2.64, MCS4 2.64, MCS5 2.04 and MCS6 1.81 and MCS7 2.42 in $\mu g/m^3$).

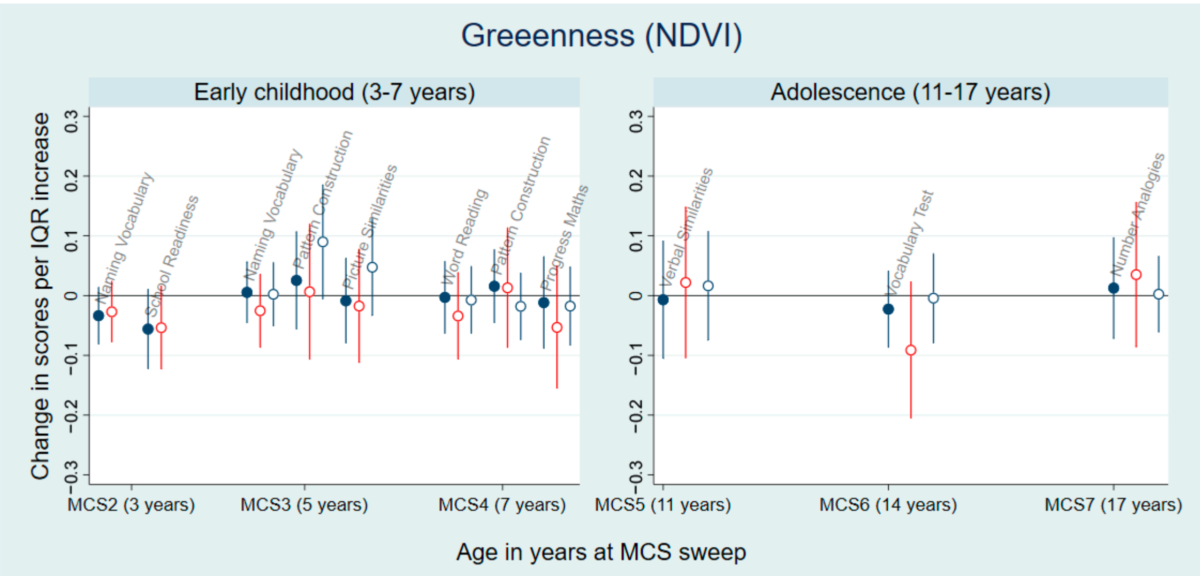

Figure 2. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per interquartile range (IQR) increase in lifetime and trajectory greenness exposure (IQR for MCS2 0.12 and MCS3–MCS7 0.11 in NDVI). Navy filled circles and lines represent point estimates and 95% confidence intervals from single environmental exposure models, open red circles and lines represent those from multi-environmental exposure models, and navy open circles and lines represent those from trajectory models (IQR for MCS3 0.12, MCS4 0.11, MCS5 0.11 and MCS6 0.1 and MCS7 0.1 in NDVI).

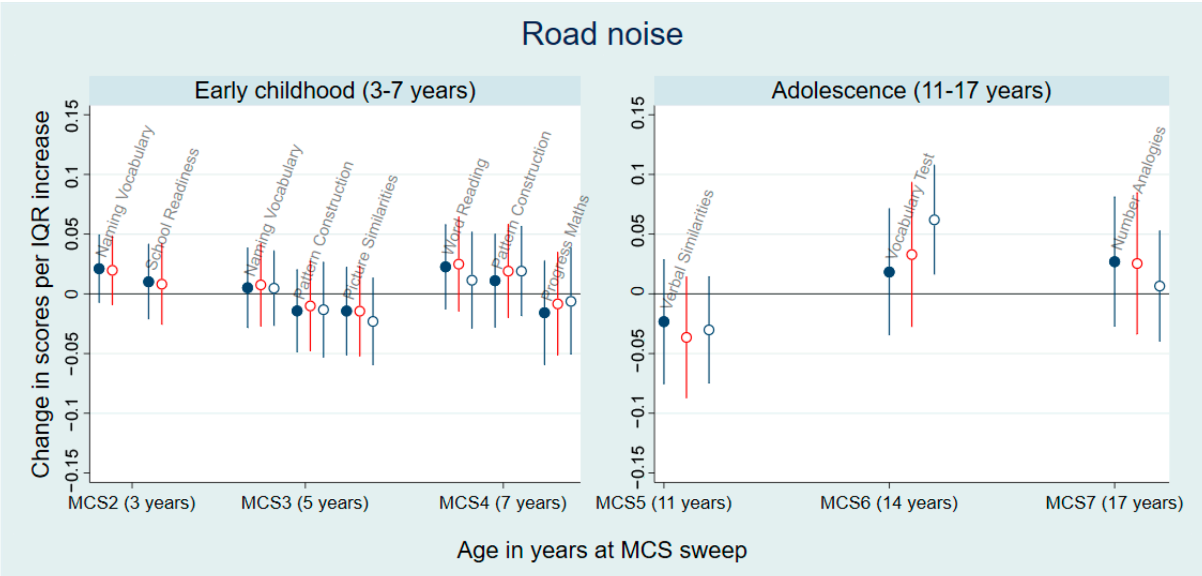

Figure 3. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per interquartile range (IQR) increase in lifetime and trajectory road noise exposure (IQR for MCS2 6.51, MCS3 6.32, MCS4 6.02, MCS5 5.68, MCS6 5.71 and MCS7 5.59 in dB). Navy filled circles and lines represent point estimates and 95% confidence intervals from single environmental exposure models, open red circles and lines represent those from multi-environmental exposure models, and navy open circles and lines represent those from trajectory models (IQR for MCS3 6.41, MCS4 6.03, MCS5 5.94 and MCS6 6.22 and MCS7 6.17 in dB).

There is little evidence of any relationships between $PM_{2.5}$, greenness, or road noise and cognitive test scores at any age in lifetime multi-exposure models (Figures 1–3). Single environmental exposure models also show no significant associations between exposures and outcomes when inter-linked environmental covariates are excluded.

3.3. Impacts on Cognitive Trajectory

The results of the trajectory models that control for performance on cognitive tests at the previous sweep are additionally presented in Figures 1–3. Similar to the findings from the main models, the trajectory analyses demonstrate no clear relationship between $PM_{2.5}$ (Figure 1), greenness (Figure 2), or road noise (Figure 3) and cognitive test scores, with the exception of $PM_{2.5}$ and road noise at different age groups. When examining the cognitive trajectory, an IQR increase in $PM_{2.5}$ exposure is associated with 0.11 (95% CI: 0.01, 0.21) higher picture similarity scores at age 5 years (MCS3) (Figure 1). An increase from the lowest quartile to the highest quartile of trajectory road noise exposure was also related to 0.06 increases (95% CI: 0.02, 0.11) in vocabulary test scores at age 14 years (MCS6) (Figure 3).

3.4. Sensitivity Analyses

The findings from the sensitivity analyses (Appendix D Figures A1–A3) support the main model results, with the exception of an unexpected negative relationship between greenness in the preceding year and school readiness at age 3 years (MCS2). Similar to the trajectory analysis, a positive association was observed between road noise and vocabulary test scores at age 14 years when school characteristics were excluded from the model (MCS6).

4. Discussion

This study utilises longitudinal cohort data from children in England to investigate the associations between lifetime $PM_{2.5}$, greenness, and road noise exposure and cognitive performance throughout childhood and adolescence. All analyses considered postcode-level environmental exposures at home and school and accounted for a comprehensive set of potential confounding factors at individual-, family-, school- and area-levels. The results from the main multi-environmental and single environmental exposure models indicate no significant relationships between any environmental determinant and standardised cognitive tests across age groups. Although unexpected beneficial associations of $PM_{2.5}$ at age 5 years and road noise at age 14 years were observed in the additional trajectory analyses, the findings largely did not detect any appreciable effects, in keeping with the main models. Coefficients for $PM_{2.5}$, greenness, or road noise did not show any consistent direction of associations across the examined analytical models. The results of this study may reflect the true nature of the relationships between children's environmental exposure and cognitive performance in this context; however, the absence of consistent findings may also be due to factors such as measurement error, a lack of power, or characteristics of the sample.

Research examining the effects of air pollution on children's cognitive development has produced findings that are similar and in contrast to the present study's results. Previous evidence from the Millennium Cohort Study (MCS) has demonstrated mixed findings; the study showed that multiple air pollutants, including $PM_{2.5}$, were related to lower Naming Vocabulary scores at age 5 and Pattern Construction scores at age 7 [46]. However, the researchers also noted that $PM_{2.5}$, amongst several other air pollutants, were associated with higher Word Reading scores at age 7. The current study may not have reproduced these results, as it was conducted on a smaller subset of children with available school information, including accounting for school-level exposure and potential confounding factors. Another large-scale, multi-pollutant study among a birth cohort of over 5000 children in the Netherlands did not detect any measurable associations between air pollutants and cognition except for some unexpected improvements in tests of reasoning and attention [60]. The researchers suggest that positive relationships between air pollutants and cognition may not represent causal effects, and may be explained by residual confounding, selection bias, or chance. Nevertheless, other lifetime exposure studies of $PM_{2.5}$ demonstrate evidence of detrimental impacts on children's cognitive development [7,12,13]. The heterogeneity in exposure and outcome measurements highlights the need for continued investigation of the nuances in the relationships between environmental factors and cognition.

Most studies of greenness exposure and cognition in children support a beneficial impact of this environmental determinant. A cohort of 27,000 children found that an interquartile range (IQR) increase in residential, lifetime greenness was related to 0.3 higher early development scores at age 6 [40]. Another study indicated that an IQR increase in greenspace within 2 km of participants' home and school was associated with 7.3–32.7 faster reaction times among 600 Flemish adolescents [30]. However, these studies employed a distinct measure of greenness, specifically, the percentage of vegetation, and included cognitive assessments contrasting with those used in the present study. Additional research demonstrating evidence of the positive effects of greenness on children's cognition have focused solely on urban areas, examined attention as a cognitive outcome, or utilised greenness data of different spatial resolutions to those used in this study [23–27,29]. Some longitudinal evidence indicates that the supportive effects of greenness on children's cognition are no longer observed when robust measures of socioeconomic status at both family- and area-levels, similar to the current study, are included in statistical models [28,61]. Other research investigating greenness and academic achievement also suggests little evidence of an association, in keeping with the findings of the current study [62,63].

Research into the harmful effects of road noise on children's cognition produces mixed results when compared more broadly to the cognitive impacts of noise exposure. To some extent, aircraft noise has been shown to negatively impact children's reading and memory performance in several studies [32–34]. Unfortunately, aircraft noise estimates were not available for this study. Research that considered ambient daytime and nighttime noise levels, similar to the present study, also demonstrated 0.3 decreases in cognitive scores per 10 dB increases among children ages 3 and 6 years old in a Brazilian cohort [35]. However, children in this sample were exposed on average to noise levels 20 to 30 dB higher than in the present study, suggesting cognitive impacts should be investigated in nosier environments. In keeping with the trajectory analysis results of the current paper, researchers examining road noise exposure found unexpected positive associations with tests of memory function completed by 9–10 year-olds in the UK, Netherlands, and Spain [32]. When examining academic achievement, a short-term study of urban home and school ambient noise exposure, including that from motorised transport, found 10 dB increases were related to 5.5 decreases in scores in French and mathematics among 8–9 year-olds [64]. Other cross-sectional research conducted in secondary schools in London found no measurable associations between ambient noise exposure and academic achievement, as in the present study [65]. Evidence suggests that the discrepancies in noise–cognition research may reflect exposure misclassification, which in the present study could be partly driven by the limited road noise data that were measured for only 73.4% of the sample [66].

Some multi-exposure research has preceded the current paper in investigating the impacts of air pollution, greenspace, and noise on children's cognition. Researchers using the MCS did not detect any consistent associations between ward-level particulate matter or greenspace at age 3 years and cognitive abilities at 3, 5, 7 or 11 years among children in England [45]. Despite improvements in the exposure estimation, the present study produced similar results. Another study, with findings akin to those of this paper, did not suggest any impact of residential $PM_{2.5}$ on cognitive function in infancy when greenness was included as a covariate in a Spanish cohort of over 400 children highly exposed to air pollution [67]. An investigation of over 29,000 Dutch children up to 4 years old demonstrated positive relationships between child development and residential greenspace at ages 1 and 2 years—outcomes and age groups that were not examined in the present study—but no effects of $PM_{2.5}$, road noise, or greenspace on any other age group in multi-environmental exposure models [68]. Research using mediation analysis generally indicates that air pollution and noise may account for some of the beneficial associations between measures of greenspace and children's cognition [38–40]. Nevertheless, other multi-environmental exposure evidence from the UK, Spain and the Netherlands shows that air pollution, greenness and road noise may be independently related to changes in children's cognitive performance [2,41–43]. It may be difficult to broadly compare results in the environment–cognition research area given diverse methodologies; however, the current study was able to replicate research using the MCS while implementing some changes in the design—inclusion of school exposure, school data, and greenness and road noise exposures—in order to identify more clearly the source of distinct findings [46].

Given that the present study utilised a nationally representative longitudinal cohort and a robust analysis approach that included a wide range of potential confounders, the limitations of this study are primarily concerned with data availability. This research project was unable to include all MCS children, as only a portion consented to data linkage with their school information in England, a factor limiting power in this study; however, it was also an advantage to consider exposure at school, where children spend a large amount of time. In addition, assumptions about the road noise exposure of approximately one quarter of the children in this study were made given the data available from Defra. It is unclear whether the findings of this study are a facet of the aforementioned limitations, or if the results represent a true absence of associations between $PM_{2.5}$ and children's cognition when rich environmental-, individual-, family-, school-, and area-level characteristics are considered in this sample.

Future research in the area could investigate the impacts of environmental exposures on other outcomes in this sample such as educational attainment or psychological wellbeing. Furthermore, studies could provide insight in the area by examining which other covariates are strongly related to cognition in this cohort. The cognitive tests in this study measure an array of verbal, non-verbal, visual, quantitative, and fluid abilities, which research suggests may be affected by chronic environmental exposures through direct and indirect pathways on mental development [7,8,31]. Given that many other environmental, social, biological, and behavioural factors impact cognitive skills, it is challenging to establish a thorough approach that can clearly identify influences on children's cognition [69]. In conclusion, this paper provides valuable information on the relationships between $PM_{2.5}$, greenness, and road noise and children's cognitive performance in the MCS that can guide future research directions into the environment–cognition link.

Author Contributions: Conceptualization, S.G., L.D., B.A. and A.M.; Methodology, S.G., L.D., B.A. and A.M.; Software, S.G., B.A. and A.M.; Validation, S.G., L.D., B.A. and A.M.; Formal Analysis, S.G., B.A. and A.M.; Investigation, S.G.; Resources, S.G., L.D. and A.M.; Data Curation, S.G.; Writing—Original Draft Preparation, S.G.; Writing—Review and Editing, L.D., B.A. and A.M.; Visualization, S.G.; Supervision, L.D., B.A. and A.M.; Project Administration, S.G., L.D., B.A. and A.M.; Funding Acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

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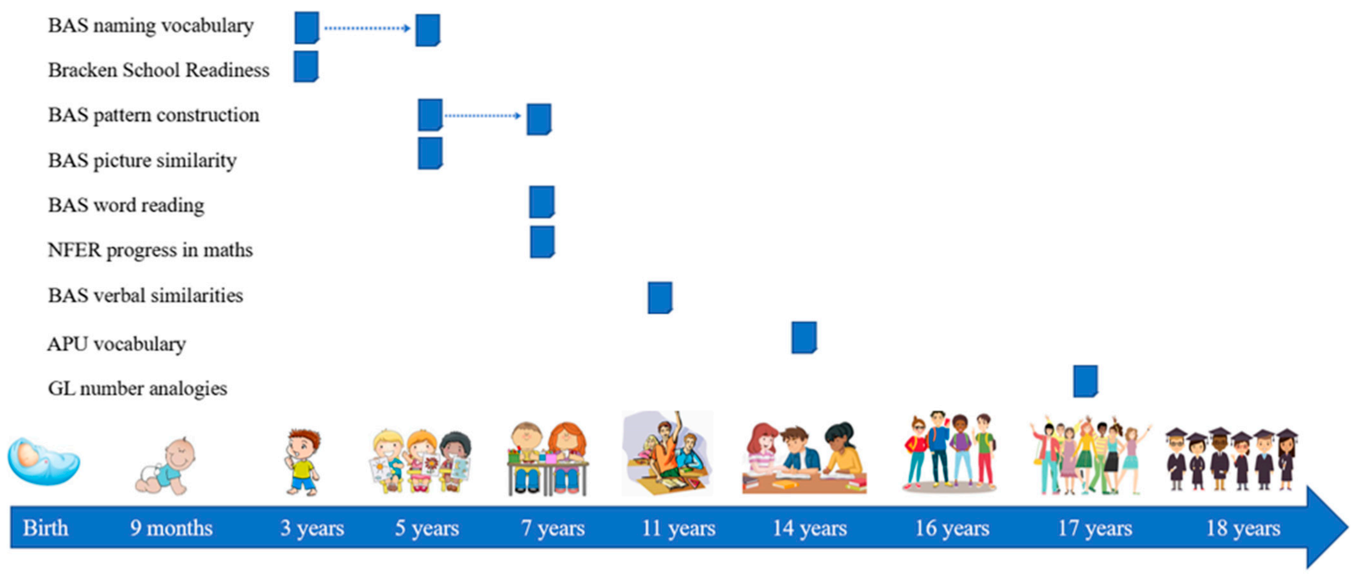
Data Availability Statement: Restrictions apply to the datasets. The datasets presented in this article are not publicly available because of data sensitivity as the data includes personally identifiable information. Requests to access the datasets should be directed to the Centre for Longitudinal Studies at University College London.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A. Cognitive Tests at Each Age Group in the Millennium Cohort Study

Blue post notes indicate at which ages each cognitive test was taken. Arrows between post notes indicate when a test was taken at more than one age group.



Appendix B. Sample Statistical Analysis Code at Age 7 Years (MCS4) in Stata

global covars "relage gender i.ethnicity i.income_quintiles i.language i.low_bweight i.breastf i.siblings mat_age i.mom_NVQ i.dad_NVQ i.region_res i.qpopden i.idacidec i.gender_code pct_lang pct_eth_white pct_eth_black pct_eth_asian pct_eth_chinese

```
pct_eth_anyoth pct_pupils_fsm_eligible pupil_teacher_ratio ta_teachers_ratio i.instype
ndvitm_mcs4periqr roadtm_mcs4periqr i.roadtm_mcs4periqr_dummy”
svyset SPTN00 [pweight=OVWT1], strata(PTTYPE2) fpc(NH2)
foreach cog_outcome in st_bas_pattern_mcs4 st_bas_read_mcs4 st_nfer_math_mcs4 {
svy: reg ‘cog_outcome’ pm25tm_mcs4periqr $covars
}
```

Appendix C

Table A1. Correlation matrix (Pearson correlation coefficients (*r*)) of preceding annual average, lifetime average and trajectory average exposures to $PM_{2.5}$, greenness, and road noise at age 7 years (MCS4, N of children = 5171).

	$PM_{2.5}$ ($\mu g/m^3$)			**Greenness (NDVI)**			**Road Noise (dB)**		
	1-Year Lag	**Lifetime**	**Trajectory**	**1-Year Lag**	**Lifetime**	**Trajectory**	**1-Year Lag**	**Lifetime**	**Trajectory**
$PM_{2.5}$									
1-year lag	1								
Lifetime	0.94	1							
Trajectory	0.99	0.97	1						
Greenness									
1-year lag	−0.52	−0.61	−0.59	1					
Lifetime	−0.52	−0.63	−0.59	0.97	1				
Trajectory	−0.47	−0.56	−0.55	0.99	0.97	1			
Road noise									
1-year lag	0.11	0.18	0.15	−0.1	−0.11	−0.1	1		
Lifetime	0.11	0.18	0.14	−0.1	−0.1	−0.08	0.93	1	
Trajectory	0.11	0.18	0.15	−0.1	−0.11	−0.1	0.98	0.92	1

Table A2. Table of regression coefficients for $PM_{2.5}$, greenness and road noise from single environmental exposure, multi-environmental exposure and trajectory models at ages 3 years (MCS2), 5 years (MCS3), 7 years (MCS4), 11 years (MCS5), 14 years (MCS6) and 17 years (MCS7).

		Cognitive Test	**$PM_{2.5}$ ($\mu g/m^3$)**	**Greenness (NDVI)**	**Road Noise (dB)**
Single exposure, β (lower, upper 95% CI)	3 years (MCS2)	School Readiness	0.03 (−0.04, 0.11)	−0.06 (−0.12, 0.01)	0.01 (−0.02, 0.04)
		Naming Vocabulary	0.03 (−0.03, 0.09)	−0.03 (−0.08, 0.01)	0.02 (−0.01, 0.05)
	5 years (MCS3)	Picture Similarity	0.02 (−0.06, 0.09)	−0.01 (−0.08, 0.06)	−0.01 (−0.05, 0.02)
		Naming Vocabulary	−0.04 (−0.11, 0.02)	0.01 (−0.05, 0.06)	0.01 (−0.03, 0.04)
		Pattern Construction	<0.01 (−0.08, 0.07)	0.03 (−0.06, 0.11)	−0.01 (−0.05, 0.02)
	7 years (MCS4)	Pattern Construction	−0.05 (−0.13, 0.03)	0.02 (−0.05, 0.08)	0.01 (−0.03, 0.05)
		Word Reading	0.07 (−0.01, 0.14)	<0.01 (−0.06, 0.06)	0.02 (−0.01, 0.06)
		Progress in Maths	0.02 (−0.08, 0.12)	−0.01 (−0.09, 0.07)	−0.02 (−0.06, 0.03)
	11 years (MCS5)	Verbal Similarities	0.06 (−0.07, 0.20)	−0.01 (−0.11, 0.09)	−0.02 (−0.08, 0.03)
	14 years (MCS6)	Vocabulary Test	0.03 (−0.05, 0.11)	−0.02 (−0.09, 0.04)	0.02 (−0.03, 0.07)
	17 years (MCS7)	Number Analogies	−0.03 (−0.13, 0.08)	0.01 (−0.07, 0.10)	0.03 (−0.03, 0.08)
Multi-exposure, β (lower, upper 95% CI)	3 years (MCS2)	School Readiness	<0.01 (−0.09, 0.09)	−0.05 (−0.12, 0.02)	0.01 (−0.03, 0.04)
		Naming Vocabulary	<0.01 (−0.07, 0.07)	−0.03 (−0.08, 0.02)	0.02 (−0.01, 0.05)
	5 years (MCS3)	Picture Similarity	−0.02 (−0.13, 0.09)	−0.02 (−0.11, 0.08)	−0.01 (−0.05, 0.02)
		Naming Vocabulary	−0.04 (−0.13, 0.05)	−0.03 (−0.09, 0.04)	0.01 (−0.03, 0.04)
		Pattern Construction	−0.04 (−0.17, 0.08)	0.01 (−0.11, 0.12)	−0.01 (−0.05, 0.03)
	7 years (MCS4)	Pattern Construction	−0.08 (−0.23, 0.08)	0.01 (−0.09, 0.11)	0.02 (−0.02, 0.06)
		Word Reading	−0.01 (−0.13, 0.11)	−0.03 (−0.11, 0.04)	0.02 (−0.01, 0.06)
		Progress in Maths	−0.06 (−0.22, 0.09)	−0.05 (−0.16, 0.05)	−0.01 (−0.05, 0.03)
	11 years (MCS5)	Verbal Similarities	0.08 (−0.10, 0.26)	0.02 (−0.10, 0.15)	−0.04 (−0.09, 0.01)
	14 years (MCS6)	Vocabulary Test	−0.08 (−0.23, 0.08)	−0.09 (−0.21, 0.02)	0.03 (−0.03, 0.09)
	17 years (MCS7)	Number Analogies	−0.02 (−0.19, 0.15)	0.04 (−0.09, 0.16)	0.03 (−0.03, 0.08)
Trajectory, β (lower, upper 95% CI)	5 years (MCS3)	Picture Similarity	0.11 (0.01, 0.21)	0.05 (−0.03, 0.13)	−0.02 (−0.06, 0.01)
		Naming Vocabulary	−0.05 (−0.12, 0.02)	<0.01 (−0.05, 0.06)	<0.01 (−0.03, 0.04)
		Pattern Construction	0.09 (−0.02, 0.19)	0.09 (−0.01, 0.19)	−0.01 (−0.05, 0.03)
	7 years (MCS4)	Pattern Construction	−0.03 (−0.12, 0.07)	−0.02 (−0.07, 0.04)	0.02 (−0.02, 0.06)
		Word Reading	0.04 (−0.04, 0.13)	−0.01 (−0.06, 0.05)	0.01 (−0.03, 0.05)
		Progress in Maths	−0.02 (−0.13, 0.10)	−0.02 (−0.08, 0.05)	−0.01 (−0.05, 0.04)
	11 years (MCS5)	Verbal Similarities	0.02 (−0.10, 0.14)	0.02 (−0.07, 0.11)	−0.03 (−0.07, 0.01)
	14 years (MCS6)	Vocabulary Test	<0.01 (−0.10, 0.10)	<0.01 (−0.08, 0.07)	0.06 (0.02, 0.11)
	17 years (MCS7)	Number Analogies	−0.08 (−0.22, 0.07)	<0.01 (−0.06, 0.07)	0.01 (−0.04, 0.05)

β, beta coefficient; CI, confidence intervals.

Appendix D

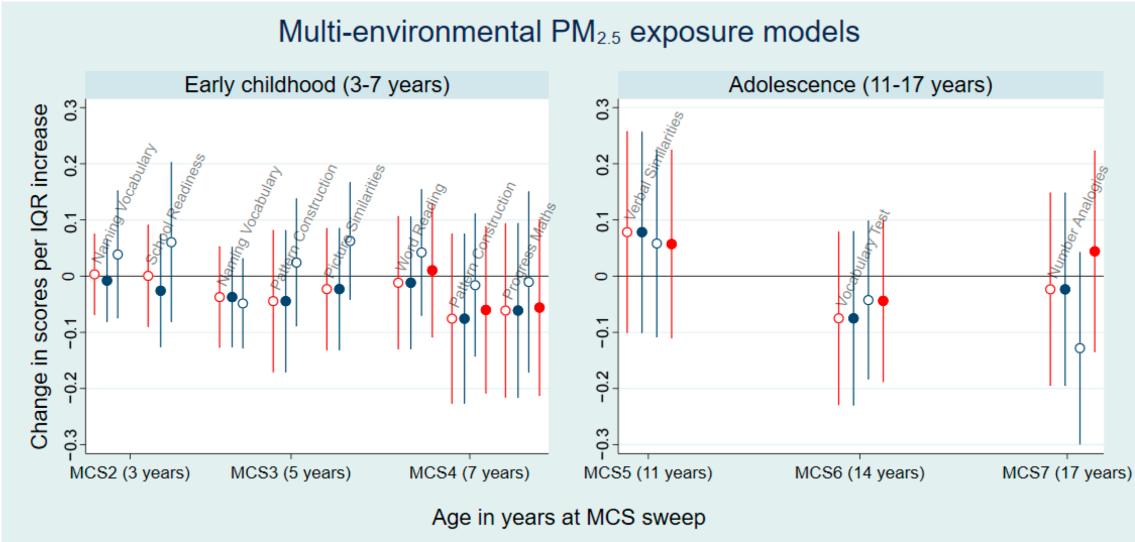


Figure A1. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per IQR increase in $PM_{2.5}$ exposure (IQR for MCS2 2.49, MCS3 2.54, MCS4 2.54, MCS5 2.24, MCS6 2.08 and MCS7 2.14 in $\mu g/m^3$) in multi-environmental exposure models. Open red circles and lines represent point estimates and 95% CIs from the main lifetime exposure models, navy filled circles and lines represent those from 1-year lag exposure models (IQR 3.2 in $\mu g/m^3$), open navy circles and lines represent those from models restricted to pupils with available road noise data and filled red circles and lines represent those from models excluding school characteristics.

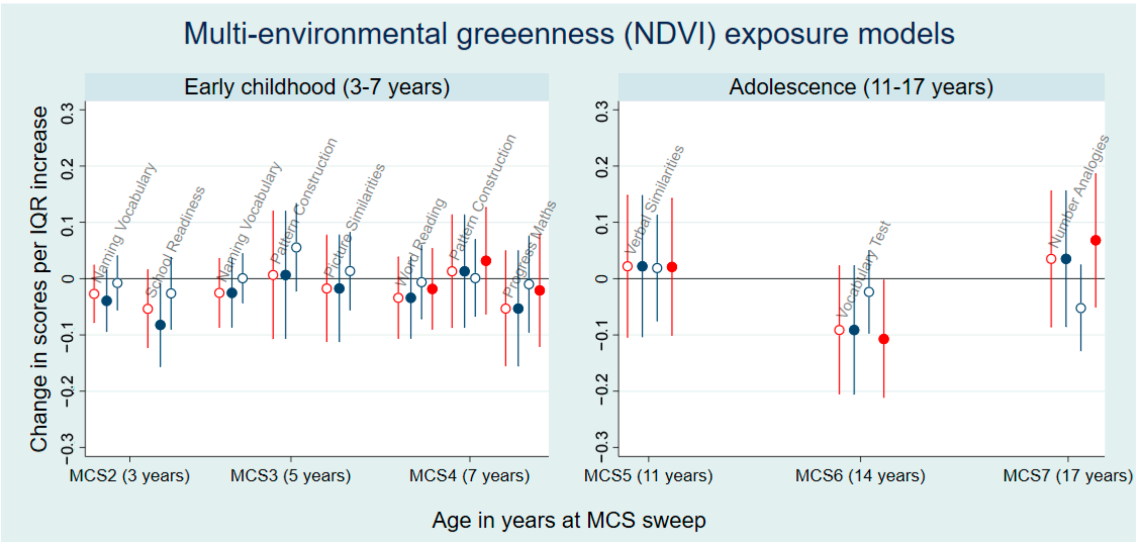


Figure A2. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per IQR increase in greenness exposure (IQR for MCS2 0.12 and MCS3–MCS7 0.11 in NDVI) in multi-environmental exposure models. Open red circles and lines represent point estimates and 95% CIs from the main lifetime exposure models, navy filled circles and lines represent those from 1-year lag exposure models (IQR 0.12 in NDVI), open navy circles and lines represent those from models restricted to pupils with available road noise data and filled red circles and lines represent those from models excluding school characteristics.

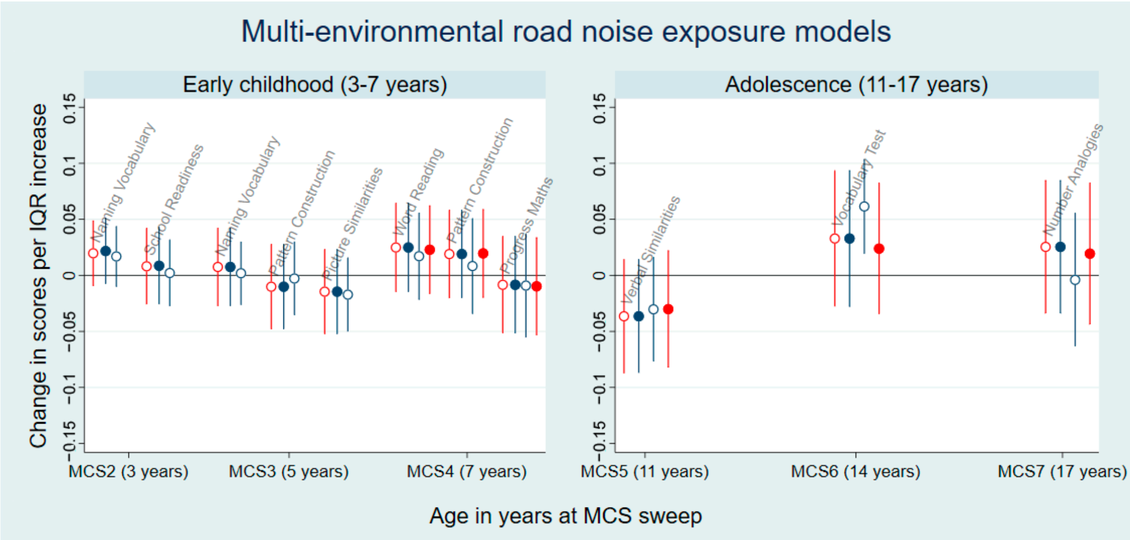


Figure A3. Estimated differences in standardised cognitive test scores at MCS2 (3 years), MCS3 (5 years), MCS4 (7 years), MCS5 (11 years), MCS6 (14 years) and MCS7 (17 years) per IQR increase in road noise exposure (IQR for MCS2 6.51, MCS3 6.32, MCS4 6.02, MCS5 5.68, MCS6 5.71 and MCS7 5.59 in dB) in multi-environmental exposure models. Open red circles and lines represent point estimates and 95% CIs from the main lifetime exposure models, navy filled circles and lines represent those from 1-year lag exposure models (IQR 6.37 in dB), open navy circles and lines represent those from models restricted to pupils with available road noise data and filled red circles and lines represent those from models excluding school characteristics.

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