Outdoor and indoor air quality and cognitive ability in young children

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Abstract

Background. This study examined outdoor and indoor air quality at ages 9 months and 3 years and their association with cognitive ability at age 3 in England and Wales. **Method**. Data from 8,198 Millennium Cohort Study children were analysed using multilevel regression. Outdoor air quality was assessed with mean annual estimates of nitrogen dioxide (NO_2) levels within a standard small area (ward). Indoor air quality was measured with parent-reports of damp or condensation in the home and exposure to secondhand smoke in the home. Cognitive ability was assessed with the British Ability Scales Naming Vocabulary subscale and the Bracken School Readiness Assessment. **Results**. In adjusted models, consistent exposure to high levels of NO_2 at age 9 months and age 3 years was associated with lower verbal ability at age 3 years. Damp or condensation and secondhand smoke in the home at either or both age 9 months or age 3 years was correlated with school readiness at age 3 years. Exposure to damp or condensation at age 3 years or at both ages and secondhand smoke at either or both age 9 months or age 3 years was correlated with verbal ability at age 3 years. **Conclusion**. Young children's exposures to indoor damp or condensation and secondhand smoke are likely to be detrimental for their cognitive outcomes. However, there do not appear to be any short-term effects of NO_2.

Keywords: air pollution; cognitive ability; damp; Millennium Cohort Study; secondhand smoke

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1. Introduction

In the last decade, research into the role of prenatal and postnatal outdoor and indoor air quality on child cognitive functioning has grown substantially (Chen, Clifford, Lang, & Anstey, 2013; Clifford, Lang, Chen, Anstey, & Seaton, 2016; Jedrychowski et al., 2011; Kicinski et al., 2015; Sánchez-Rodríguez, Santiago, Arronte-Rosales, Vargas-Guadarrama, & Mendoza-Nunez, 2006; Tonne, Elbaz, Beevers, & Singh-Manoux, 2014; Wang et al., 2009). Prenatal exposures to outdoor air pollutants including particulate matter (PM2.5), nitrogen dioxide (NO_2), polycyclic aromatic hydrocarbons (PAHs) and benzene have been linked to infant psychomotor and cognitive functioning (Chiu et al., 2016; Lertxundi et al., 2015; Perera et al., 2006). A number of studies have also found effects of postnatal exposures to traffic-related pollutants in school-aged children. For example, higher levels of black carbon predicted decreased cognitive functioning in middle childhood in a US city sample (Suglia, Gryparis, Wright, Schwartz, & Wright, 2008). In a study of school-aged children in China, researchers found significant differences in performance on sensory, motor and psychomotor functioning assessments for children living in more and less (NO_2) polluted areas (Wang et al., 2009). A more recent study in Spain found significant associations between general markers of road traffic pollution and slower cognitive growth in a large sample of children (Sunyer et al., 2015). Another study examined primary school children's recent and chronic exposure to PM at home and in the classroom (Saenen et al., 2016). It showed links between recent exposure at home and visual information processing speed as well as between chronic exposure at home and measures of attention. However, not all studies have found significant effects. Clark et al. (2012) examined the associations between noise levels, air pollution and cognition and health in children residing in areas surrounding a major airport in London, UK. In that study, moderate levels of air pollution did not predict child cognition. It is not easy to

compare these studies, however, given their variations in pollutant and cognitive measures and differences in confounding variables accounted for.

It is also difficult to estimate the true effect of outdoor air pollution on child cognition as most studies do not account for indoor sources of air pollution which may confound these associations (Clifford et al., 2016). Children, especially young children, spend the majority of their time indoors which may protect them somewhat from harmful exposures to outdoor air pollutants. However, air pollutants generated indoors such as those from activities like smoking, cooking, heating, and use of paints, varnishes and cleaning products may adversely affect child cognition (Clifford et al., 2016). Indoor air quality may also be related to outdoor air quality as pollutants from outdoors (e.g., by industrial processes and traffic emissions) may migrate inside the home through windows or other forms of ventilation.

It seems however that we know similarly little about the role of indoor air quality in cognitive functioning in children (Chen et al., 2013; Jedrychowski et al., 2011), although the few studies into this to date have shown promising findings. For example, a cohort study carried out in Poland found that persistent exposure to mould in the home was related to poorer cognitive ability in children of school age (Jedrychowski et al., 2011). Another study explored the impact of indoor NO_2 exposure from gas appliances on child cognition in Spain, and found a dose-response relationship between NO_2 levels and cognitive outcomes including overall cognitive function, verbal abilities and executive functioning (Morales et al., 2009). About young children we know even less. Even among the studies into the role of exposures to secondhand smoke (SHS) in cognition in young children (Jedrychowski et al., 2009; Julvez et al., 2007; Lee et al., 2011), those linking indoor air quality to early childhood outcomes (Chen et al., 2013; Yolton, Mizuo, Moriya, Oshio, Sugawara, & Takeda, 2005), are few. They also tend to produce null findings after adjustment for appropriate confounders.

Effect mechanisms

The lack of research into the role of air quality in cognition in young children is unfortunate in view of the evidence that air quality is implicated in physiological mechanisms which may directly affect cognition. For example, exposure to air pollutants may deleteriously affect young children's cognitive ability through promoting neuroinflammation and oxidative stress (Calderón-Garcidueñas et al., 2013; Guarnieri & Balmes, 2014). Experimental studies have shown that air pollutants can penetrate the blood brain barrier and cause direct neuronal and white matter injury as well as systematic inflammation that adversely impacts the developing nervous system (Block et al. 2012). Furthermore, exposure to air pollutants can exacerbate or cause asthma and wheezing (Esposito et al., 2014; Guarniari & Balmes, 2014). Respiratory problems such as asthma and allergy, in turn, can impede upon children's cognition (Blackman & Gurka, 2007).

With regard to indoor exposures in particular, damp or condensation often results in moulds and bacteria that can produce microscopic airborne particles (Górny et al., 2002). Some of these particles contain allergens or chemicals with the potential to induce neuroinflammation. Secondhand smoke has high concentrations of many toxic chemicals that are harmful to the brain (Chen et al., 2013). For example, carbon monoxide in the bloodstream can reduce oxygen in the brain (Mezzacappa, Buckner, & Earls, 2011) and nicotine can affect the cholinergic system (Slotkin, 1999; 2004) which may result in overstimulation of neurons implicated in learning and memory.

The present study

The existing research has several limitations that this study was carried out to address. First, no studies, to our knowledge, have explored the role of postnatal exposures to air pollution in pre-school children when the developing brain may be most susceptible to environmental toxins (Block et al., 2012). Second, the studies to date utilised relatively small samples and most are cross-sectional. Third, a major omission in the literature is the

simultaneous exploration of *both* outdoor and indoor air quality in child cognition. Fourth, the existing research neglected to examine the nature of the relationship between pollution and child cognition (e.g., whether the relationship is dose-response or not), assuming air pollution is unsafe at all levels (Lanphear, 2015). Last, no study has accounted for the amount of green space in their neighbourhood, which may confound the association between outdoor air pollution and children's cognition. Green space has been shown to improve air quality (Beckett, Freer-Smith, & Taylor, 1998) and to be related to children's cognitive functioning including attentional capacities (Wells, 2000) and academic performance (Wu et al., 2014).

The present study aims to address these aforementioned gaps in the literature through a secondary analysis of data from the Millennium Cohort Study (MCS), a longitudinal survey of 19,519 UK children born during the year 2000 or shortly thereafter and their families. It explores the nature of the relationship between neighbourhood-level (i.e., ward[1]) NO_2, and two indicators of indoor air quality – damp or condensation and secondhand smoke - measured twice in early childhood (at ages 9 months and 3 years) and child cognitive ability at age 3 years (when first measured in MCS) in England and Wales. NO_2 is mainly caused by the combustion of fossil fuels (Katsouyanni, 2003). Nitrogen oxides are emitted as NO which quickly reacts with oxygen and ozone forming NO_2. NO_2 is emitted primarily from road traffic and energy production processes. Its main sources are diesel engines. In the UK, the level of NO_2 has regularly exceeded the legal levels set by EU air quality standards, such as those set out in the EU Ambient Air Quality Directive and the fourth Daughter Directive. In 2013, 34.5% of licensed cars in the UK were diesel

[1]Electoral wards are the key building block of UK electoral geography (http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/administrative/england/electoral-wards-divisions/index.html). The average population is around 5,500, though counts can vary substantially. Census area statistical (CAS) wards in particular are used in this study. They are a type of ward created for the 2001 census.

(Department for Transport, 2014). This has become a major concern for citizens as well as policymakers, particularly in London where levels are highest. Therefore, identifying air pollution effects on young children has important implications for UK transport policy. At the same time, air quality standards in the UK currently apply to outdoor rather than indoor air. Hence, there is a case for developing guidelines for indoor air quality based on our understanding of the risks posed by indoor air pollutants.

2. Method

2.1. Sample

The Millennium Cohort Study (MCS; www.cls.ioe.ac.uk/mcs) is a longitudinal survey drawing its sample from all births in the UK over a year, beginning on 1 September 2000 (Plewis, 2007). To date, six sweeps (waves) of data have been carried out. A total of 19,519 children participated in at least one of these six sweeps. The MCS sample is disproportionately stratified, firstly by country, and then type of electoral ward. The sample design over-represented families living in areas of high child poverty, areas with high proportions of ethnic minority populations across England, and the three smaller UK countries. In MCS, children and their families were sampled from 338 wards across the UK (Plewis, 2007). Ethical approval was gained from NHS Multi-Centre Ethics Committees, and parents gave informed consent before interviews took place.

We used data from Sweeps 1 and 2 (at ages 9 months and 3 years, respectively). We started with the total sample (n = 19,519) and retained only singletons and first born twins/triplets resulting in n = 19,244, making the number of children equal to the number of families. Our analytic sample comprised children who lived in England or Wales in both Sweeps 1 and 2 and who had complete data on all variables used in the analysis including outdoor and indoor air quality indicators, cognitive functioning at age 3 and all covariates (n = 8,198).

2.2. Measures

Cognitive ability at age 3 was measured with scores on two assessments, verbal ability and school readiness. *Verbal ability* was assessed with the British Ability Scales II Naming Vocabulary test, which assesses the spoken vocabulary of children aged 2 years 6 months to 7 years 11 months. The test items consist of coloured pictures of objects shown to the child, one at a time. The test measures expressive language ability, vocabulary knowledge of nouns, general knowledge and language development and stimulation. In MCS, standardised scores on the Naming Vocabulary scale are adjusted for the child's age group. They have a mean of 50 and a standard deviation of 10 (ranging 10-80). The Bracken School Readiness Assessment was used to measure *school readiness*. This assessment comprises several sub-tests which evaluate concepts relating to colours, letters, numbers/counting, sizes, comparisons and shapes. These concepts predict readiness for formal education. The test is appropriate for children aged 2 years 6 months to 8 years. In this study we used the age-adjusted school readiness composite standard score, which is the total number of correct answers on all six sub-tests. The score has a mean of 100 and a standard deviation of 15 (ranging 56-149). Higher scores on both cognitive tests indicate higher ability.

NO_2 was measured with data from the Multiple Environmental Deprivation Index (MEDIx), an ordered measure of physical environmental deprivation that represents the balance of pathogenic and salutogenic characteristics in each ward (Richardson, Mitchell, Shortt, Pearce, & Dawson, 2010; Shortt, Richardson, Mitchell, & Pearce, 2010; http://cresh.org.uk/cresh-themes/environmental-deprivation/medix-and- medclass/). In MEDIx, NO_2 is measured with annual mean concentrations [in micrograms (one-millionth of a gram) per cubic meter air or $\mu g/m^3$] within each ward. Means are population-weighted using output area units and cover the years 1999-2003. These data are taken from 1 km grids, modelled from National Atmospheric Emissions Inventory data. The annual mean values

have been converted to deciles across all wards in the UK prior to linking them with MCS Sweeps 1 (age 9 months) and 2 (age 3 years). The annual mean concentration of NO_2 is less than 9.26 $\mu g/m^3$ in the bottom decile and greater than 33.89 $\mu g/m^3$ in the top decile. Note that the annual mean legal limit for NO_2 is 40 $\mu g/m^3$.

To assess non-linear associations between NO_2 and child outcomes, NO_2 concentrations were also measured categorically (low/medium and high) with the top three deciles as the high group and the bottom seven deciles as the low/medium group. A high level of NO_2 refers to an annual mean concentration equal to or higher than 29.91 $\mu g/m^3$ and a low/medium level refers to an annual mean concentration lower than 29.91 $\mu g/m^3$. Long-term exposure to air pollutants (i.e., at both age 9 months and age 3 years) was captured using the categories of low/medium and high resulting in the following groups: 1) low/medium polluted area at 9 months and 3 years, 2) high polluted area at 9 months and 3 years, 3) high polluted area at 9 months and low/medium polluted area at 3 years, 4) low/medium polluted area at 9 months and high polluted area at 3 years.

Indoor air quality at age 9 months and 3 years was measured by the mother's report of whether there was a *damp or condensation* problem at home and whether the child was exposed to *secondhand smoke (SHS)*. At age 9 months, mothers were asked whether anyone smokes in the same room as the baby and at age 3 years, they were asked whether anyone smokes in the same room as the child. Long-term exposure to damp or condensation and SHS (i.e., at both age 9 months and age 3 years) was captured using the following groups: exposure at 9 months and 3 years, 2) exposure at 9 months but not 3 years, 3) exposure at 3 years but not 9 months, 4) no exposure at 9 months or 3 years.

Two neighbourhood factors – percentage of *green space* and *urbanicity* - were also measured in the study. The percentage of green space was measured with data from MEDIx.

The percentage captures the combined coverage of all spaces larger than 5 m^2 (excluding private gardens) for each ward. Therefore green spaces such as neighbourhood greenery, parks, playing fields and forests/woodlands are included. In MEDIx, the percentage of greenspace is at ward-level. It was estimated by combining land use data from the Generalised Land Use Database (Office of the Deputy Prime Minister, 2001) and the Coordination of Information on the Environment (EEA, 2000). In MCS, the percentages of ward-level greenspace using this measure have been converted to deciles across all wards in the UK. The lowest decile corresponds to areas with 0-21% green space per ward and the top decile corresponds to areas with 94-95% green space per ward. A settlement was defined as *urban* if it had a population greater than 10,000. We used a binary variable that specified if the family lived in an urban area when the cohort child was either age 9 months or age 3 years.

Key covariates were child- and family-level. The child-level covariates were *gender, age* (in years), *ethnicity* (white, black, Indian, Pakistani/Bangladeshi, mixed and other) and *low birth weight* (<2.5 kg). The family-level covariates (measured at age 3) were *maternal education* (university degree or not), *maternal psychological distress,* measured with a summary score on the Kessler Psychological Distress scale (K6), a 6-item screening instrument of psychological distress (Kessler et al., 2003), *residential stability* (same address in Sweep 1 and Sweep 2), and *maternal involvement* [frequency of reading to the child, on a 6-point scale ranging from 1 (every day) to 6 (not at all)].

2.3. Data analysis

We started with descriptive analyses, including a bias analysis comparing the analytic and non-analytic samples and correlations among the key study variables. We then fitted 2-level multilevel linear regression (random intercept) models for each outcome (verbal ability and school readiness). This approach enabled us to avoid the underestimation of standard

errors due to the hierarchical nature of our data in having children (Level 1) nested in areas (Level 2). We accounted for area clustering at the level of ward on which the MCS survey design was built. As the intercept was allowed to vary randomly, Level 1 captures individual variations in outcomes at the intercept between children within wards (between-child variation) and Level 2 estimates variations in outcomes at the intercept for children between wards (between-ward variation).

Our neighbourhood environment variables (air pollution, green space and urbanicity) were all measured at ward-level to align with the clustering in MCS. In all adjusted models, the MCS sampling stratum was controlled to account for the disproportionate stratification of the MCS survey design. In each of the four UK countries, families were oversampled from areas with high child poverty ('disadvantaged') and (in England only) areas with high proportions of ethnic minorities ('ethnic'). As children from England and Wales were included in our sample, we adjusted for five strata: England-ethnic, England-disadvantaged, England-advantaged (those who did not reside in 'disadvantaged' or 'ethnic' wards), Wales-disadvantaged and Wales-advantaged.

We fitted three models for each of the two cognitive outcomes and each of the three ways of measuring NO_2 (therefore, there was a total of 18 models). The first (Model 1) was the variance components model or the 'null' model, which captured the variances attributable to children and wards prior to adjusting for any variables. Model 2 explored the effects of outdoor air pollution and indoor air quality (exposure to SHS and having a damp or condensation problem in the home) adjusting for neighbourhood variables (green space, urbanicity and sampling strata) and child's age at the time of the cognitive assessments. Model 3 added the family-level background variables associated with neighbourhood selection and home condition (maternal psychological distress, maternal education and maternal involvement) and additional child covariates (low birth weight, gender and

ethnicity). These adjusted models (Model 2 and 3) were run separately for the two approaches to measuring outdoor air pollution exposure in infancy (age 9 months): 1) deciles, to capture linear effects of NO_2 (2 models, one for each outcome), and 2) categories of high vs. medium/low levels of NO_2, to capture non-linear effects (2 models, one for each outcome). Additionally, all models were run for each outcome for the longitudinal exposures (NO_2, damp/condensation and SHS across age 9 months and age 3 years). In this part of the analysis, the models also adjusted for whether the family moved between child ages 9 months and 3 years. This was in order to control for the effects of moving itself on cognitive ability as a change in air pollution across sweeps for a given family implies a change in that family's neighbourhood resulting from a home move.

3. Results

3.1 Descriptive analyses

Children in the analytic sample lived, on average, in wards in England and Wales with higher annual mean concentrations of NO_2 (Table 1). They also lived in relatively less green neighbourhoods across the distribution of wards in the UK. The majority lived in urban areas (82%) and most did not change address (67%). Around 14% and 12% of mothers reported having damp or condensation problems and exposing their child to SHS in the home, respectively. To further examine the selection bias in our analytic sample, we compared the study variables in the analytic sample (n=8,198) and in the non-analytic sample (n=11,046) (results available on request). Verbal ability and school readiness scores were higher for the children in the analytic sample. The children in the two samples differed in the majority of the key covariates except for maternal psychological distress. Specifically, children in the analytic sample were more likely to belong to the white ethnic group, live in rural areas with more green space yet higher NO_2 and lower rates of SHS exposure. Those in the analytic sample had more educated and involved mothers. In our sample, statistically significant

correlations (Supplementary Table 1) were found between NO_2 and cognitive scores and between indoor air quality (damp or condensation and SHS) and cognitive scores, but these were weak to moderate (ranging -.06 to -.17).

Table 1

Descriptives of study variables in the analytic sample (n = 8,198)

	n	**%**
Child		
Female	4,066	49.94
Ethnicity		
White	7,280	91.15
Black	198	1.95
Indian	156	1.29
Pakistani/Bangladeshi	246	1.82
Mixed	264	3.18
Other	54	0.62
Low birth weight	465	5.54
Parent/household		
Mother is university-educated	2,950	37.10
Family did not move between S1 and S2	5,615	67.62
Neighbourhood		
NO_2 groups (at S1)		
Low/medium	4,080	48.01
High	4,118	51.99
NO_2 exposure at S1 and S2		
Low/medium (S1 and S2)	3,958	46.34
High (S1 and S2)	3,824	48.24
High (S1), low/medium (S2)	294	3.75
Low/medium (S1), high (S2)	122	1.67
Urban	6,849	81.69
Indoor air quality		
Damp or condensation	1,136	13.53
Secondhand smoke	997	11.64
	n	**M(SD)**
Child		
Verbal ability	8,198	50.78(13.16)
School readiness	8,198	105.83(14.39)
Age (years)	8,198	3.12(0.18)
Parent/household		
Maternal psychological distress	8,198	3.21(3.45)
(Low) frequency mother reads to child	8,198	1.65(0.96)

Neighbourhood		
NO_2 deciles	8,198	7.15(2.23)
Green space deciles	8,198	4.41(2.28)

Note: S1 = Sweep 1, S2 = Sweep 2. Percentages and means weighted. Ns unweighted.

3.2 Multilevel modelling

The analytic sample comprised 8,198 children clustered in 273 wards, with an average of 30.0 children in each (number of children within wards ranged from 3 to 147). In the variance components model for verbal ability, the child-level variance (Level 1) was 103.66 (SE = 1.65) and the variance due to clustering in wards (Level 2) was 10.62 (SE = 1.30). Therefore, the intraclass correlation (ICC) was .093 suggesting that 9.3% of the variance in verbal ability scores is attributable to ward. For school readiness, the child-level variance (Level 1) was 213.76 (SE = 3.39) and the variance due to clustering in wards (Level 2) was 26.39 (SE = 3.04). The ICC was .110 suggesting that 11.0% of the variance in school readiness scores is attributable to ward.

3.2.1 Indoor and outdoor exposure at age 9 months and child cognitive ability at age 3 years (Models 2 and 3)

Table 2 shows Model 2 and 3 results when NO_2 levels were measured in deciles. Exposure to NO_2 levels in infancy was not significantly associated with verbal ability or school readiness at age 3 in Model 2 (Table 2). (Examinations of earlier models with NO_2 deciles showed that NO_2 was significantly predictive of both verbal ability and school readiness before adjusting for green space in the ward and the MCS strata, respectively.) However, both damp/condensation and SHS in the home in infancy were significantly associated with lower verbal ability and lower school readiness. Living in an urban area and amount of green space in the ward were unrelated to verbal ability and school readiness. The between-ward variance remained significant but decreased in this model, resulting in an ICC

of only .045 for verbal scores and .071 for school readiness scores. Hence, only 4.5% and 7.1% of the variance in the respective scores was attributed to ward.

In Model 3 (Table 2), damp or condensation was no longer significantly associated with verbal ability but it remained a significant predictor of school readiness. SHS also retained its significance for both cognitive scores. All child and family covariates added in Model 3 were significantly associated with verbal ability and school readiness. Females had higher verbal and school readiness scores and those with low birth weight had lower scores in both domains. Pakistani/Bangladeshi and black children had lower school readiness scores and all non-white ethnic groups had lower verbal scores at this age relative to white children. Maternal education was related to higher scores and maternal psychological distress and low frequency of reading to the child were predictive of lower scores. The between-ward variance (which was significant) decreased further in this model, resulting in an ICC of only .030 for verbal scores and .060 for school readiness scores. Hence, only 3.0% and 6.0% of the variance in the respective scores was attributed to wards. This means that some of the child and family covariates explained part of the differences in scores between wards.

Next, we looked at the effects of living in an area with high vs. medium or low concentrations of NO_2. Living in an area with a high level of NO_2 in infancy did not predict significantly lower verbal scores at age 3 or school readiness scores in Models 2 or 3 (Supplementary Tables 2 and 3). For damp or condensation and SHS exposure, comparable results were found as in the models using NO_2 exposures in deciles.

3.2.2. Indoor and outdoor air pollution exposures at age 9 months and age 3 years and child cognitive ability at age 3 years (Models 2 and 3)

In Model 2 (not shown), living in an area with high levels of NO_2 in infancy and at age 3, compared to living in an area with medium/low NO_2 concentration at both ages, was

related to lower verbal ability (b = -1.22, SE = 0.44) but not school readiness (b = -1.21, SE = 0.72) scores at age 3. Living in an area with high concentrations of NO_2 in infancy and moving to an area with medium/low concentration at age 3 significantly predicted higher verbal ability scores (b = 2.57, SE = 0.74) and school readiness scores (b = 3.74, SE = 1.10). In Model 3 (Table 3), these three significant NO_2 effects remained.

In Model 2 (not shown), exposure to damp or condensation at both age 9 months and 3 years (verbal ability: b = -2.17, SE = 0.67; school readiness: b = -4.39, SE = 0.95), at age 9 months only (verbal ability: b = -1.04, SE = 0.37; school readiness: b = -1.93, SE = 0.52) and at age 3 years only (verbal ability: b = -2.25, SE = 0.60; school readiness: b = -3.82, SE = 0.85), compared to not experiencing damp or condensation at either age, was associated with both outcomes. In the fully adjusted models, these effects remained significant except for the effect of exposure at age 9 months on verbal ability (Table 3).

In Model 2 (not shown), SHS exposure at any and both ages predicted verbal ability and school readiness scores. Specifically, SHS exposure at both age 9 months and 3 years (verbal ability: b = -3.70, SE = 0.44; school readiness: b = -8.12, SE = 0.62), at age 9 months only (verbal ability: b = -2.33, SE = 0.55; school readiness: b = -5.16, SE = 0.78) and at age 3 years only (verbal ability: b = -1.93, SE = 0.39; school readiness: b = -5.00, SE = 0.56), compared to no SHS in the home at either age, was associated with both outcomes. In the fully adjusted models, these effects remained significant (Table 3).[2]

[2] Previous studies have shown that postnatal SHS effects are attenuated when adjusting for whether the mother smoked in pregnancy (Chen et al., 2013). Therefore, we adjusted for whether the mother smoked in pregnancy in Model 3, but the significant effects of SHS remained.

Table 2

Effects of NO_2 (deciles) and indoor air quality at age 9 months on verbal ability and school readiness at age 3 years

	Verbal ability				School readiness			
	Model 2		Model 3		Model 2		Model 3	
	Coeff. (SE)	95% CI	Coeff. (SE)	95% CI	Coeff. (SE)	95% CI	Coeff. (SE)	95% CI
				Fixed effects				
Constant	49.660***(2.093)	[45.558, 53.762]	45.301***(1.970)	[41.439, 49.163]	101.264***(3.086)	[95.216, 107.312]	95.001***(2.917)	[89.282, 100.719]
NO_2 (deciles)	-0.050(0.100)	[-0.246, 0.145]	0.018(0.086)	[-0.151, 0.186]	-0.062(0.162)	[-0.256, 0.380]	0.097(0.146)	[-0.189, 0.383]
Damp or condensation	-1.262***(0.331)	[-1.910, -0.615]	-0.589(0.314)	[-1.205, 0.027]	-2.504***(0.473)	[-3.214, -1.534]	-1.439***(0.447)	[-2.316, -0.562]
SHS	-3.065***(0.351)	[-3.753, -2.377]	-1.727***(0.340)	[-2.394, -1.060]	-6.558***(0.502)	[-7.542, -5.574]	-3.863***(0.484)	[-4.812, -2.914]
Green space	0.119(0.098)	[-0.074, 0.311]	0.072(0.087)	[-0.099, 0.242]	-0.051(0.152)	[-0.349, 0.247]	-.109(0.139)	[-0.381, 0.164]
Urban area	-0.383(0.562)	[-1.484, 0.717]	-0.247(0 .495)	[-1.216, 0.723]	-1.046(0.879)	[-2.769, 0.676]	-0.623(0.800)	[-2.190, 0.945]
Age	1.009(0.571)	[-0.111, 2.128]	1.618***(0.539)	[0.562, 2.675]	2.840***(0.818)	[1.236, 4.443]	3.822***(0.770)	[2.314, 5.331]
Female			2.543***(0.213)	[2.125, 2.961]			3.620***(0.303)	[3.025, 4.214]
Ethnicity (Ref: white)								
Mixed			-1.367**(0.622)	[-2.585, -0.148]			-0.169(0.885)	[-1.903, 1.566]
Indian			-5.326***(0.864)	[-7.019, -3.632]			-2.281(1.238)	[-4.708, 0.145]

Pakistani/Bangladeshi			-11.783***(0.768)	[-13.287,-10.278]			-8.499***(1.113)	[-10.680, -6.318]
Black			-5.288***(0.779)	[-6.815, -3.761]			-5.647***(1.118)	[-7.838, -3.456]
Other			-7.452***(1.342)	[-10.081, -4.822]			-2.850(1.910)	[-6.594, 0.895]
Low birth weight			-2.145***(0.463)	[-3.053, -1.237]			-2.933***(0.658)	[-4.223, -1.643]
(Low) frequency mother reads to child			-1.667***(0.107)	[-1.877, -1.456]			-2.828***(0.153)	[-3.128, -2.529]
Mother is university-educated			2.728***(0.239)	[2.259, 3.197]			5.260***(0.342)	[4.589, 5.930]
Maternal psychological distress			-0.140***(0.029)	[-0.198, -0.083]			-0.304***(0.042)	[-0.386, -0.222]
Area stratum (Ref: England-advantaged)								
England-disadvantaged	-2.266***(0.471)	[-3.190, -1.342]	-0.929**(0.400)	[-1.713, -0.146]	-4.647***(0.784)	[-6.674, -3.532]	-2.539***(0.701)	[-3.913, -1.165]
England-ethnic	-7.492***(0.794)	[-9.049, -5.936]	-1.937***(0.724)	[-3.355, -0.519]	-9.199***(1.321)	[-11.789, -6.609]	-3.973***(1.240)	[-6.403, -1.542]
Wales-advantaged	-0.940(0.729)	[-2.369, 0.489]	-0.569(0.622)	[-1.787, 0.649]	-3.266**(1.198)	[-5.613, -0.918]	-2.700**(1.069)	[-4.795, -0.605]
Wales-disadvantaged	-2.322***(0.584)	[-3.466, -1.177]	-1.122**(0.499)	[-2.100, -0.143]	-4.243***(0.959)	[-6.123, -2.363]	-2.178**(0.859)	[-3.862, -0.494]
				Random effects				
Ward-level intercept variance (Level 2)	4.790***(0.771)	[3.494, 6.567]	2.784***(0.569)	[1.865, 4.157]	15.846***(2.077)	[12.256, 20.489]	11.812***(1.657)	[8.973, 15.550]
Child-level intercept variance (Level 1)	102.561***(1.629)	[99.417,105.804]	91.796***(1.460)	[88.979, 94.702]	208.522***(3.310)	[202.135,215.112]	184.439***(2.928)	[178.788,190.269]

*Note: *p < .05; **p < .01; ***p < .001.* SHS = secondhand smoke. Area strata adjust for the MCS oversampling of families from areas of high child poverty and with high proportions of ethnic minorities (in England only). The ward-level intercept variance captures the variability in verbal ability and school readiness scores between wards and the child-level intercept variance captures the extent to which children's verbal ability and school readiness scores differ within wards.

Table 3

Effects of NO_2 (high vs. low/medium) at age 9 months and 3 years on verbal ability and school readiness at age 3 years (Model 3)

	Verbal ability		**School readiness**	
	Coeff. (SE)	**95% CI**	**Coeff. (SE)**	**95% CI**
			Fixed effects	
Constant	44.448***(1.948)	[40.631,48.266]	94.473***(2.829)	[88.928, 100.019]
NO_2 (Ref: low/medium at S1 and S2)				
NO_2 (high at S1 and S2)	-0.787*(0.385)	[-1.542, -0.032]	-0.945(0.659)	[-2.236, 0.346]
NO_2 (high at S1 and low/medium at S2)	1.396*(0.678)	[0.067, 2.726]	1.862(1.028)	[-0.152, 3.876]
NO_2 (low/medium at S1 and high at S2)	-0.886(0.915)	[-2.680, 0.907]	-0.968(1.305)	[-3.526, 1.590]
Damp or condensation (*Ref: neither at S1 nor at S2*)				
Damp or condensation (at S1 and S2)	-1.501**(0.637)	[-2.750, -0.252]	-3.172***(0.904)	[-4.944, -1.400]
Damp or condensation (at S1 and not at S2)	-0.410(0.349)	[-1.094, 0.274]	-1.014*(0.496)	[-1.986, -0.042]
Damp or condensation (at S2 and not at S1)	-1.487**(0.566)	[-2.597, -0.377]	-2.459***(0.804)	[-4.035, -0.883]
Secondhand smoke *(Ref: neither at S1 nor at S2)*				
SHS (at S1 and S2)	-2.179***(0.424)	[-3.011, -1.348]	-4.957***(0.603)	[-6.138, -3.776]
SHS (at S1 and not at S2)	-1.224**(0.521)	[-2.245, -0.204]	-3.109***(0.739)	[-4.558, -1.660]
SHS (at S2 and not at S1)	-0.972**(0.376)	[-1.710, -0.235]	-2.991***(0.534)	[-4.039, -1.943]
			Random effects	
Ward-level intercept variance (Level 2)	2.611***(0.549)	[1.730, 3.942]	11.323***(1.617)	[8.558, 14.981]
Child-level intercept variance (Level 1)	91.464***(1.454)	[88.658, 94.359]	183.114***(2.908)	[177.502, 188.903]

Note: ***$p < .001$. S1 = Sweep 1 (age 9 months), S2 = Sweep 2 (age 3 years), SHS = secondhand smoke. Model fully adjusted (Model 3) for the following child- and family-level covariates: Age (in years), green space, urban area, gender, ethnicity, low birth weight, frequency of mother reading to child, maternal education, maternal psychological distress and area stratum and family moves. The ward-level intercept variance captures the variability in verbal ability and school readiness scores between wards and the child-level intercept variance captures the extent to which children's verbal ability and school readiness scores differ within wards.

4. Discussion

This study explored longitudinally the role of both outdoor and indoor air quality in cognition (verbal ability and school readiness) in early childhood, in a large, nationally representative sample in England and Wales. It also tested the dose-response relationship between outdoor air quality and child cognition, to attempt to shed light on whether any amount of air pollution is unsafe or whether a higher level of pollution is required to see detrimental effects. It examined these associations adjusting for a range of key confounders including neighbourhood greenery and urbanicity, and family factors associated with selection into neighbourhoods and households.

Approximating outdoor air quality with levels of NO_2 in the neighbourhood, we found that there were no linear or non-linear effects of the concentration of NO_2 in infancy (age 9 months) on scores on either measure of cognition at age 3. However, exposure to high levels of NO_2 at *both* age 9 months and age 3 years and moving from an area with a high level of NO_2 to one with a low/medium level had associations with verbal ability scores at age 3, even after adjustments for important confounders including indoor air quality, greenery, urbanicity, ethnicity, maternal education, maternal involvement and maternal psychological distress. That is, being exposed to high levels of NO_2 at age 9 months and age 3 years was associated with verbal ability scores prior to school age. Moreover, moving from a more polluted to a less polluted area in early childhood was related to higher verbal ability scores. The NO_2 effect sizes were, however, relatively small. The mostly null associations between NO_2 and cognition are contrary to those found in most of the few studies that have explored traffic-related air pollution effects on cognitive functioning in children of school-age (Saenen et al., 2016; Suglia et al., 2008; Sunyer et al., 2015; Wang et al., 2009). Here we explored, for the first time, these associations in younger children. Also, of these few studies with school-age children, two (Saenen et al., 2016; Sunyer et al., 2015) found links with working memory

and inattentiveness and one (Wang et al., 2009) demonstrated associations with response time, motor coordination and psychomotor stability. These outcomes (compared to verbal ability and school readiness) may be more related to the kinds of functions in the brain affected by neuroinflammation and oxidative stress, caused by air pollution. However, Suglia et al. (2008) *did* find links with a range of verbal and non-verbal assessments more closely related to our measures, but in a small sample (n = 202) of older children (ages 8-11).

We also found that, even after accounting for a range of confounders, exposure to damp or condensation in infancy was associated with school readiness, and SHS in the home in infancy predicted both verbal ability and school readiness. Exposure to damp and condensation in infancy *and* at age 3, as well as at age 3 only, was related to verbal ability and school readiness. Exposures to SHS at any age was negatively related to verbal ability and school readiness. Damp and condensation in the home can cause mould which has been related to poorer cognitive ability in school-aged children (Jedrychowski et al., 2011). Our findings regarding SHS are contrary to those of the few studies of SHS exposure and cognitive functioning in young children (Jedrychowski et al., 2009; Julvez et al., 2007; Lee et al., 2011) showing null associations between the two after adjustment for appropriate confounders including maternal smoking in pregnancy. Our study found consistent and robust relationships between SHS and our two cognitive scores, even after adjusting for maternal smoking in pregnancy.

These findings may have implications for the development of UK indoor air quality guidelines, particularly those which aim to target problems with damp and condensation and exposure to secondhand smoke. The developing brain is vulnerable to toxins (Block et al. 2012) and therefore exposures in the early years may have particularly negative impacts. Therefore, measures to reduce young children's exposures to poor indoor air quality may have long-term benefits. On the other hand, although there is plenty of evidence for the

negative impact of outdoor air pollution (measured, as in our study, with NO_2 levels) on various child and adult outcomes that warrants reductions in NO_2 emissions in urban areas (Guarnieri & Balmes, 2014; Schwartz et al., 2005), our findings do not provide strong evidence on NO_2 effects to support these reductions.

This study has some important limitations, however. First, our findings may be due to selection bias, a pervasive problem of contextual effects research. Second, although there is some evidence for the effect of mother's prenatal exposures to air pollution, mould and SHS on child's neurodevelopment (Perera et al., 2006), we could not consider them because of the lack of data on them in MCS. Therefore, it is possible that associations between postnatal exposures and child cognition may be explained by exposures in the prenatal period. However, we did check whether smoking in pregnancy explained the SHS effect in our models, and it did not, nor was it a predictor of either cognitive outcome. Third, our measurement of air pollution was an average of annual mean concentrations across a 4-year period applied to the neighbourhoods where children and their families lived at each of the two waves of MCS. Therefore, changes in the levels of pollutants are likely muted by the 4-year average. Fourth, a finer spatial resolution would have allowed for an assessment of the more immediate pollutants around the home. We were also not able to account for any spillover effects from adjacent areas. Fifth, although we attempted to capture the indoor air quality of the cohort child's home through self-reported proxies (damp or condensation problem and whether the child was exposed to secondhand smoke in the home) we were unable to measure it directly, e.g., by the level of pollutants, such as NO_2, present. We also lacked additional information about the indoor atmosphere of the home such as the use/presence of a woodstove, candles and fragrances, cleaning supplies and cooking methods. Sixth, we were unable to capture noise exposures. Most air pollutants such as NO_2 are mainly due to road traffic, and road traffic causes noise. A number of studies have demonstrated that

traffic noise exposure impairs learning and cognition, particularly reading comprehension (Clark et al., 2012; Haines et al. 2001; Hygge, Evans, & Bullinger, 2002; Stansfeld et al., 2005). Lastly, the measure of secondhand smoke crudely measured whether or not anyone smoked in the same room as the child. It would have been desirable to also know the number of cigarettes smoked per day to gauge the extent of exposure. Future research should attempt to address these limitations.

In conclusion, we found, in a nationally representative sample, that young children's verbal ability and school readiness may be impaired by exposure to damp or condensation and secondhand smoke in the home. However, we found little evidence for cognitive differences due to differences in outdoor NO_2 levels. It seems that consistent exposure to higher levels of NO_2 over the first few years of life may be needed to detect differences in cognition for those exposed and unexposed to ambient air pollution. Further research should explore these relationships using outdoor air pollution data measured on finer spatial and time scales and with more detailed information on air pollutants indoors.

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