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Prenatal and Childhood Traffic-Related Air Pollution Exposure and Childhood Executive Function and Behavior

Maria H. Harris[1], **Diane R. Gold**[2,3], **Sheryl L. Rifas-Shiman**[4], **Steven J. Melly**[3], **Antonella Zanobetti**[3], **Brent A. Coull**[5], **Joel D. Schwartz**[2,3], **Alexandros Gryparis**[6], **Itai Kloog**[3,7], **Petros Koutrakis**[3], **David C. Bellinger**[3,8], **Mandy B. Belfort**[9], **Thomas F. Webster**[1], **Roberta F. White**[1], **Sharon K. Sagiv**[1,10], and **Emily Oken**[4]

[1]Department of Environmental Health, Boston University School of Public Health, Boston, MA, USA

[2]Channing Laboratory, Brigham and Women's Hospital, Boston, MA, USA

[3]Department of Environmental Health, Harvard T.H. Chan School of Public Health, Boston, MA, USA

[4]Department of Population Medicine, Harvard Medical School and Harvard Pilgrim Health Care Institute, Boston, MA, USA

[5]Department of Biostatistics, Harvard T.H. Chan School of Public Health, Boston, MA, USA

[6]Department of Hygiene, Epidemiology and Medical Statistics, University of Athens Medical School, Athens, Greece

[7]The Department of Geography and Environmental Development, Ben-Gurion University of the Negev, Beer Sheva, Israel

[8]Department of Neurology, Boston Children's Hospital, Harvard Medical School, Boston, MA, USA

[9]Division of Newborn Medicine, Boston Children's Hospital, Harvard Medical School, Boston, MA, USA

[10]Center for Environmental Research and Children's Health, School of Public Health, University of California at Berkeley, Berkeley, CA, USA

Abstract

Background—Traffic-related air pollution exposure may influence brain development and function and thus be related to neurobehavioral problems in children, but little is known about windows of susceptibility.

Corresponding author: Maria H Harris, PhD, Center for Environmental Research and Children's Health, School of Public Health, University of California at Berkeley, 1995 University Ave., Suite 265, Berkeley, CA 94720 USA, Telephone: (510) 642-9508, mariaharris@berkeley.edu.

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Aims—Examine associations of gestational and childhood exposure to traffic-related pollution with executive function and behavior problems in children.

Methods—We studied associations of pre- and postnatal pollution exposures with neurobehavioral outcomes in 1,212 children in the Project Viva pre-birth cohort followed to mid-childhood (median age 7.7 years). Parents and classroom teachers completed the Behavior Rating Inventory of Executive Function (BRIEF), and the Strengths and Difficulties Questionnaire (SDQ). Using validated spatiotemporal models, we estimated exposure to black carbon (BC) and fine particulate matter ($PM_{2.5}$) in the third trimester of pregnancy, from birth to 3 years, from birth to 6 years, and in the year before behavioral ratings. We also measured residential distance to major roadways and near-residence traffic density at birth and in mid-childhood. We estimated associations of BC, $PM_{2.5}$, and other traffic exposure measures with BRIEF and SDQ scores, adjusted for potential confounders.

Results—Higher childhood BC exposure was associated with higher teacher-rated BRIEF Behavioral Regulation Index (BRI) scores, indicating greater problems: 1.0 points (95% confidence interval (CI): 0.0, 2.1) per interquartile range (IQR) increase in birth-age 6 BC, and 1.7 points (95% CI: 0.6, 2.8) for BC in the year prior to behavioral ratings. Mid-childhood residential traffic density was also associated with BRI score (0.6, 95% CI: 0.1, 1.1). Birth-age 3 BC was not associated with BRIEF or SDQ scores. Third trimester BC exposure was not associated with teacher-rated BRI scores (−0.2, 95% CI: −1.1, 0.8), and predicted lower scores (fewer problems) on the BRIEF Metacognition Index (−1.2, 95% CI: −2.2, −0.2) and SDQ total difficulties (−0.9, 95% CI: −1.4, −0.4). $PM_{2.5}$ exposure was associated with teacher-rated BRIEF and SDQ scores in minimally adjusted models but associations attenuated with covariate adjustment. None of the parent-rated outcomes suggested adverse effects of greater pollution exposure at any time point.

Conclusions—Children with higher mid-childhood exposure to BC and greater near-residence traffic density in mid-childhood had greater problems with behavioral regulation as assessed by classroom teachers, but not as assessed by parents. Prenatal and early childhood exposure to traffic-related pollution did not predict greater executive function or behavior problems; third trimester BC was associated with lower scores (representing fewer problems) on measures of metacognition and behavioral problems.

Keywords

Traffic; air pollution; black carbon; executive function; neurodevelopment

1. Background

An accumulating body of evidence suggests that early life exposure to traffic-related air pollution can affect the developing brain (Block et al. 2012; Calderon-Garciduenas et al. 2014; Costa et al. 2014). The authors of a recent review identified polycyclic aromatic hydrocarbons (PAH), fine particulate matter with aerodynamic diameter ≤ 2.5 μm ($PM_{2.5}$), and nitrogen dioxides as air pollutants potentially harmful to neuropsychological development in children (Suades-Gonzalez et al. 2015). Recent epidemiologic studies have examined whether air pollution exposure increases risk for adverse behavioral development including behaviors related to attention deficit hyperactivity disorder (ADHD). Higher

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childhood exposure to particulate matter with aerodynamic diameter ≤ 10 μm (PM_{10}, of which one component is $PM_{2.5}$) was associated with increased prevalence of ADHD among school age children in India, where vehicular emissions are one important source of particulate pollution (Siddique et al. 2011). In a Boston cohort of 7-14 year olds, lifetime (since birth) childhood exposure to black carbon (BC), traffic-related particles commonly used as a marker of traffic pollution, was associated with worse performance on computerized assessments of attention (Chiu et al. 2013). Among Cincinnati children, higher exposure to traffic-related elemental carbon in the first year of life predicted greater hyperactive behaviors at age 7 (Newman et al. 2013). In China, 8-10 year old children from a more polluted city performed worse on assessments of attention, motor skills, and sensory function than children from a less polluted city (Wang et al. 2009). Seven-11 year old children in Barcelona with higher exposure to elemental carbon, black carbon and nitrogen dioxide at school displayed greater behavioral problems (Forns et al. 2015); children with higher traffic-related air pollution exposure also displayed slower improvements in attentiveness and working memory over a 12 month period (Sunyer et al. 2015). Prenatal exposure to PAH, air pollutants related to traffic and other forms of combustion, predicted increased attention problems and anxiety/depression behaviors at age 6-7 and greater ADHD-related behaviors at age 9 among children in New York City (Perera et al. 2012; Perera et al. 2014). While findings to date suggest a link between traffic-related pollution and neurobehavioral outcomes, additional research is needed to identify particular components of traffic-related pollution that are most influential, developmental windows that are most sensitive, and aspects of childhood neurobehavior that are most affected. To investigate these questions in a large prospective cohort followed from pregnancy onwards, we examined several measures of prenatal and childhood exposure to traffic-related pollution [BC and $PM_{2.5}$ estimated at the residence level, residential proximity to major roadways, and near-residence traffic density] in relation to ratings of children's executive function and behavior problems as reported by parents and classroom teachers.

2. Materials and Methods

2.1 Study population

Participants were drawn from Project Viva, a longitudinal pre-birth cohort of 2,128 mother and child pairs (Oken et al. 2015). Mothers were enrolled from April 1999 to November 2002 during initial prenatal visits at eight obstetrical offices of Atrius Harvard Vanguard Medical Associates, a multi-specialty group practice with locations in urban and suburban Eastern Massachusetts. To be eligible, mothers needed to be ≤22 weeks gestation at enrollment (median=9.9 weeks), able to communicate in English, report no plans to move out of the study area, and give birth to live singleton infants. Viva staff administered a range of health and developmental assessments at prenatal visits and periodic follow-up visits during infancy and childhood, and participants completed annual questionnaires regarding health-related behaviors. Mothers reported their residential address at enrollment and each follow-up encounter (at mid-pregnancy, delivery, six months, and annually from age 1 forward). At a Project Viva study visit in mid-childhood (median age 7.7 years, range 6.6–10.9), mothers and classroom teachers reported behavior of child participants using validated questionnaires. The present study included participants with at least one behavioral rating

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scale and one measure of traffic-related pollution exposure (n=1,212). Depending on the analysis, final sample sizes ranged from 758 to 1,185. The Institutional Review Board of Harvard Pilgrim Health Care approved this analysis. All mothers provided written informed consent and children provided verbal assent at the mid-childhood visit.

2.2. Traffic-related pollutant exposures

We geocoded participants' residential addresses using ArcGIS 10.1 with Street MapTM North America (ESRI, Redlands, CA), aerial photographs, and internet resources. Based on these addresses, and using daily estimates from validated spatiotemporal land use regression models, we assessed mean exposure of participants to BC and $PM_{2.5}$ during four periods: the third trimester of gestation, the first three years of life, the first six years of life, and the year preceding behavioral ratings. The third trimester mean was selected *a priori* to represent prenatal exposure because third trimester exposure estimates were available for a larger number of participants than first or second trimester exposures; the third trimester is also the period of gestation when brain development is most rapid (Tau and Peterson 2010). 90 percent of mothers remained at the same residential address from enrollment through date of delivery.

Methodologies for the pollutant models have been described (Gryparis et al. 2007; Kloog et al. 2012; Zanobetti et al. 2014). Briefly, the BC model incorporated data on area land use, traffic density, meteorology, and daily BC measurements from a central monitoring site on the roof of the Harvard Countway Library of Medicine in Boston, and BC measurements from 148 permanent and temporary BC monitors operating in Eastern Massachusetts between January 1999 and August 2011 (Gryparis et al. 2007; Zanobetti et al. 2014). The $PM_{2.5}$ model used satellite aerosol optical depth measurements at the 10 km × 10 km grid scale for the years 2000-2010 (from the Moderate Resolution Imaging Spectroradiometer aboard the Earth Observing System satellites), and also included daily ground-level measurements of $PM_{2.5}$ from United States Environmental Protection Agency and Interagency Monitoring of Protected Visual Environments networks, along with data on area land use, meteorology, and locations of major roads and other sources of $PM_{2.5}$ (Kloog et al. 2012). We estimated BC and $PM_{2.5}$ exposures for all participants who lived in the areas covered by the models (Eastern Massachusetts for the BC model, New England for the $PM_{2.5}$ model) for at least 90% of the days in a given exposure period.

2.3 Residential distance to major roadway and near-residence traffic density

We calculated residential distance to a major roadway and near-residence traffic density at two timepoints: child's birth date (to represent prenatal and perinatal exposure) and date of mid-childhood behavioral ratings (to represent proximal exposure). Using ArcGIS, we measured the distance in meters from each geocoded residence to nearest major roadway (US Census feature class A1 or A2, denoting major federal and state roads likely to have significant volumes of traffic). Near-residence traffic density was defined as the length in kilometers of all roads within 100 meters of a residence, multiplied by the traffic counts for those roads (vehicles/day) [as in (Zeka et al. 2008)]. We accessed traffic count data from the Massachusetts Department of Transportation through the Office of Geographic Information (MassGIS).

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2.4 Neurobehavioral outcomes

Parents and teachers were asked to complete two validated behavioral rating scales of child participants: the Behavior Rating Inventory of Executive Function (BRIEF) and the Strengths and Difficulties Questionnaire (SDQ). The BRIEF evaluates executive function, assessing behaviors including planning and organization, working memory, inhibition of inappropriate impulses, emotional control, and ability to re-evaluate and shift problem solving approaches and is validated and standardized for use in children aged 5-18 (Gioia et al. 2000). Trained Project Viva staff scored completed BRIEF questionnaires according to published guidelines to generate two index scores (Metacognition (MI) and Behavioral Regulation (BRI)), and one overall Global Executive Composite score (GEC), which combines the MI and BRI. The MI, BRI, and GEC scores were each standardized to mean=50, standard deviation (SD)=10 using published reference data; higher scores represent greater problems (Gioia et al. 2000). The SDQ assesses problem behaviors in four categories (hyperactivity, emotional problems, conduct problems, and peer problems) (Goodman 1997), and has good agreement with the Child Behavior Checklist (Goodman and Scott 1999; Stone et al. 2010). It is frequently used in research and clinical settings and is valid and reliable among children aged 4-16 (Vostanis 2006). SDQ questionnaires were scored by trained Project Viva staff, yielding sub-scores in each behavioral category and a measure of total behavioral difficulties (possible scores range from 0–40 with higher scores representing greater problems).

2.5 Covariates

We accessed information on participant demographics and health-related behaviors from Project Viva questionnaires and interviews. We collected data on children's birth weight and date of birth from hospital medical records. At the mid-childhood study visits, we administered the Kaufman Brief Intelligence Test (KBIT-2) to mothers to determine maternal full scale IQ (Kaufman and Kaufman 2004). Mothers also completed the Home Observation for Measurement of the Environment-Short Form (HOME-SF), a validated measure of emotional support and cognitive stimulation in the child's home (Frankenburg and Coons 1986). We analyzed maternal blood lead level using blood samples provided by mothers (n=630) during pregnancy. We also accessed available clinical blood lead measures from early childhood from medical records for a subset of child participants (n=434). Using data from the 2000 US Census and geocoded addresses, we recorded median household income for the census tract of residence at the time of behavioral ratings (United States Census Bureau, 2000).

2.6 Statistical analyses

We evaluated correlation among exposures, outcomes, and covariates by calculating Spearman rank correlation coefficients. We ran separate multivariate linear regression models to assess relationships of each exposure measure (BC, $PM_{2.5}$, distance to major roadway, near-residence traffic density) with each outcome score (parent- and teacher-rated BRIEF GEC, BRIEF MI, BRIEF BRI and SDQ total difficulties) for each exposure window (third trimester, first three years of life, first six years of life, and year prior to behavioral ratings for BC and $PM_{2.5}$, birth address and address at the time of behavioral ratings for

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distance to distance to major roadway and near-residence traffic density). We also conducted sensitivity analyses examining effect estimates for year-long exposure intervals between birth and age 6 for BC and $PM_{2.5}$.

Although outcome scores had skewed distributions, model residuals were approximately normal. Sensitivity analyses employing standard errors robust to violations of normality and homoscedasticity assumptions confirmed the results of linear models.

Initial models were minimally adjusted for child sex and age at behavioral ratings. Primary models were adjusted for child sex and age at behavioral ratings, and a set of covariates hypothesized to be potential confounders based on prior knowledge. These covariates included: duration of any breastfeeding (months up to 12), maternal IQ, parity (0, 1, ≥2), age at enrollment (<25, 25-34, ≥35 years), marital/cohabitation status (yes/no), education (≥college graduate/<college graduate), race/ethnicity (black, white, Hispanic, Asian, other), smoking status (never, former, smoked during pregnancy), exposure to secondhand smoke during pregnancy (<1 hour/≥1 hour per week), and alcohol consumption during pregnancy (g/day), paternal education (≥college graduate/<college graduate), presence of a gas stove in household at infancy (yes/no), annual household income at time of behavioral ratings (< $40K, $40-70K, $70-150K, ≥$150K), median income for census tract of residence at the time of behavioral ratings, HOME-SF score, maternal blood lead level from pregnancy (μg/dL), and child blood lead level in early childhood (μg/dL). We additionally adjusted third trimester BC and $PM_{2.5}$ models for seasonal trends (using sine and cosine functions of the date of the mid-childhood visit when behavioral ratings were completed) (Schwartz et al. 1991). Birth weight and gestational age were hypothesized to be potential causal intermediates between prenatal traffic exposure and neurobehavioral outcomes, so we did not adjust for these variables in primary models, but included gestational age (in weeks) and birth weight/gestational age z-score (Oken et al. 2003) as covariates in sensitivity analyses.

In initial analyses, BC, $PM_{2.5}$ and near residence traffic density exposures were assessed linearly as continuous variables and scaled by the interquartile range (IQR) of each variable. Distance to major roadway was assessed as a three category variable (<50 m, 50– <200 m, and ≥200 m), reflecting previously observed patterns of spatial distributions for important traffic-related pollutants in relation to major roadways, with rapid decay as distance increases (Hart et al. 2009; Karner et al. 2010; Zhu et al. 2002). To assess the assumption of linearity for BC, PM, and near-residence traffic density models, we ran generalized additive models with cubic regression splines for continuous exposures (with three degrees of freedom), adjusted for the full set of primary covariates. Splines suggested consistent patterns of non-linearity in associations between childhood BC exposure and BRIEF and SDQ scores; based on visual inspection of observed patterns we re-ran models for BC exposures using two-section piecewise linear models for mean BC concentration with a knot at 0.5 $\mu g/m^3$. Splines for PM and traffic density models did not suggest consistent non-linear dose-response patterns.

To reduce bias and improve model precision (through increased sample size), we imputed missing covariates using a chained equation multiple imputation model (PROC MI in SAS) including exposure and outcome variables, study covariates, and other potential predictors.

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We generated 50 imputed data sets including all Project Viva participants (n=2,128) (White et al. 2011). We combined the imputed data sets using PROC MIANALYZE (Rubin 2004). Final models included participants with imputed covariate data, but participants with missing measurements of exposure or outcome for a given exposure-outcome analysis were excluded from that analysis.

Prior investigators have suggested that sex (Chiu et al. 2013) and maternal education (Newman et al. 2013) may modify associations between air pollution exposure and behavioral outcomes. We assessed potential effect measure modification by child sex and maternal education level by re-running primary models for BC, $PM_{2.5}$ and near-residence traffic density exposure with cross-product interaction terms for exposure by sex or exposure by maternal education (≥college graduate/<college graduate). We did not assess effect measure modification in major roadway proximity models because statistical power was limited by the low numbers of participants in most highly exposed category.

We performed analyses in SAS Version 9.3 (SAS Institute Inc, Cary, NC) and R Version 3.1.3 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1 Participant characteristics and traffic-related pollution exposures

Table 1 outlines characteristics of the 1,212 study participants, overall and by category of BC exposure (≤0.5μg/m^3 vs. >0.5μg/m^3) in the year prior to behavioral ratings. On average, participants with higher mid-childhood BC exposure had higher teacher-rated and slightly higher parent-rated SDQ and BRIEF scores (representing greater behavioral and executive function problems), lower birth weight and birth weight/gestational age z-score, lower maternal IQ, lower levels of maternal and paternal education, lower household income, higher rates of gas stove ownership (a potential source of indoor air pollution), and lower neighborhood median income. Mothers of participants with higher mid-childhood BC exposure were more likely to be black or Hispanic and less likely to be white. Correlations between parent and teacher ratings on the same instrument were moderate (Spearman r=0.35 for the BRIEF GEC, 0.44 for the SDQ), while intra-rater correlations of BRIEF GEC with SDQ scores were higher (Spearman r=0.78 for teachers, 0.69 for parents). Participants excluded due to missing exposure or outcome data (n=916, or 43% of the originally enrolled 2,128) had somewhat lower birth weight (3,429 versus 3,485 g), shorter duration of breastfeeding (4.2 versus 6.3 months), higher rates of maternal smoking in pregnancy (17 versus 10%) and somewhat lower levels of parental education and household income than included participants, and were more likely to be black or Hispanic and less likely to be white (Supplemental Table 1). Distributions of covariates in the original and the imputed data sets were very similar (Supplemental Table 1).

Table 2 summarizes levels of exposure to traffic-related pollution. BC exposure in the year prior to behavioral ratings [mean (SD)=0.47 (0.14) μg/m^3] was positively correlated with third trimester mean BC (Spearman r =0.58), birth-age 6 BC (0.88), and all exposure periods of $PM_{2.5}$ exposure and near-residence traffic density. As expected, BC exposure also tended to be higher among participants living <50 m or 50 to <200m from a major roadway compared to ≥200 m from a major roadway. Excluded participants had similar levels of exposure to traffic-related pollution in the prenatal period (or at birth address) as included participants (Supplemental Table 1).

3.2 BC exposure and neurobehavioral scores

In minimally adjusted (child age and sex-adjusted) linear models, an IQR increase in BC exposure (0.20 μg/m^3) in the year prior to behavioral ratings was associated with higher teacher-rated scores (indicating greater problems) on the BRIEF BRI (3.2 points, 95% confidence interval (CI): 2.3, 4.1), MI (2.1, 95% CI: 1.2, 3.1) and SDQ (1.1, 95% CI: 0.6, 1.7). In models adjusted for the full set of covariates, associations of BC in the year prior to behavioral ratings and teacher-rated scores were attenuated (BRI: 1.7 points per IQR increase, 95% CI: 0.6, 2.8; MI: 0.5, 95% CI: −0.6, 1.6; SDQ: 0.1, 95% CI: −0.5, 0.8). Patterns of association were similar for birth-age 6 BC exposure (Table 3). Birth-age 3 BC exposure was not associated with BRIEF or SDQ scores. In sensitivity analyses examining exposure during each year of life from birth to age 6, associations of BC exposure with teacher-rated BRIEF BRI scores were stronger in years 4, 5, and 6 than in years 1, 2, and 3 (see Supplemental Figure 2).

Higher third trimester BC was associated with higher teacher-rated BRI in minimally adjusted models (1.2 points per IQR increase, 95% CI: 0.3, 2.2) but showed no association with teacher-rated BRI scores and an association with lower (better) MI scores (−1.2, 95% CI: −2.2, −0.2) in covariate-adjusted models (Table 3).

Covariate-adjusted spline models suggested non-linear relationships between mean BC in the year prior to behavioral ratings and BRIEF and SDQ scores; visual inspection of plotted splines suggested inflection points at 0.4– 0.6 μg/m^3 (see Supplemental Figures 1a-d) (patterns were generally similar for birth-age 6 BC). Covariate-adjusted piecewise linear regression models showed that among participants with year prior to behavioral ratings mean BC exposure above 0.5 μg/m^3, a 0.2 μg/m^3 increase in BC was associated with larger increases in BRIEF scores than seen in linear models: 4.8 points (95% CI: 1.7, 7.8) for the BRI and 2.9 points (95% CI: −0.3, 6.2) for the MI. Teacher-rated SDQ scores were also higher among these participants: 2.0 points per 0.2 μg/m^3 BC (95% CI: 0.2, 3.7) (Table 4). Among participants with mean exposure in the year prior to behavioral ratings below 0.5 μg/m^3, greater BC was not associated with teacher-rated BRIEF or SDQ scores. Higher third trimester, birth-age 3 and birth-age 6 BC exposure were associated with higher (worse) teacher-rated BRIEF scores among participants with BC exposures >0.5 μg/m^3, but appeared associated with lower (better) scores among participants with BC exposures ≤0.5 μg/m^3 (Table 4).

In minimally adjusted linear models, BC exposures in the year prior to behavioral ratings or the birth-age 6 period appeared associated with slightly higher parent-rated BRIEF and SDQ scores, but were not associated with parent-rated behavioral scores in covariate-adjusted models (Table 5). In covariate-adjusted linear models, third trimester BC exposure appeared associated with slightly lower parent-rated BRIEF scores (representing better executive function) (Table 5). Covariate-adjusted piecewise linear models showed no association for third trimester, birth-age 3, or birth-age 6 BC exposure with parent-rated BRIEF scores in

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either BC exposure category, but suggested that an increase of 0.2 μg/m^3 BC in the year prior to behavioral testing was associated with higher parent-rated BRIEF BRI (2.5 points; 95% CI: 0.0, 5.1) and GEC scores (2.7 points; 95% CI: 0.1, 5.3) among participants with mean exposure >0.5 μg/m^3 and somewhat lower parent-rated BRIEF scores among participants with mean exposure ≤0.5 μg/m^3 (Table 6).

3.3 $PM_{2.5}$ exposure and neurobehavioral scores

Mean $PM_{2.5}$ exposures in the third trimester, birth-age 3 period, birth-age 6 period, and year prior to behavioral ratings were associated with higher teacher-rated BRIEF and SDQ scores in minimally adjusted models, but not in covariate-adjusted models (Table 3). $PM_{2.5}$ exposures did not appear associated with parent-rated BRIEF scores in either model, with the exception of associations of higher mean birth-age 3 and birth-age 6 $PM_{2.5}$ with higher parent-rated BRIEF BRI and SDQ scores in minimally adjusted models (Table 5).

3.4 Traffic exposure measures and neurobehavioral scores

Near-residence traffic density at birth address was not associated with teacher- or parent-rated BRIEF scores in minimally adjusted or covariate-adjusted models. Higher near-residence traffic density at mid-childhood address was associated with higher teacher-rated BRI and MI scores in minimally adjusted models, but associations attenuated with adjustment for covariates, and only BRI score remained associated with mid-childhood near-residence traffic density (Table 3). Higher mid-childhood near-residence traffic density was associated with slightly higher parent-rated BRI scores in minimally adjusted models, but not in covariate-adjusted models (Table 5).

Teacher-rated BRIEF scores were higher among participants living <50 m from a major roadway at birth compared to those living ≥200 m in both minimally adjusted and covariate-adjusted models, but confidence intervals for estimates were wide (owing to the small number of participants in the <50 m category; n=34) and contained the null value (Table 3). In minimally adjusted models, there was also a suggestion of higher teacher-rated BRIEF scores among children living close to major roadways in mid-childhood, but associations attenuated following adjustment for covariates (Table 3). Parent-rated BRIEF scores were not associated with roadway proximity at birth, but scores were lower (suggesting better executive function) among children living <50 m from a major roadway in mid-childhood compared to those living ≥200 m in covariate-adjusted models (Table 5).

3.6 Sensitivity analyses

Models additionally adjusted for birth weight and birth weight for gestational age z-score yielded results very similar to primary covariate-adjusted models (not shown). There were no consistent patterns of effect measure modification by child sex or maternal education level in observed associations (not shown).

4. Discussion

In our study cohort of Eastern Massachusetts children, higher average BC exposure from birth through age 6 and in the year proximal to behavioral ratings predicted greater problems with behavioral regulation (a component of executive function involving inhibitory control of emotion and impulses) as assessed by classroom teachers in mid-childhood (median age 7.7) using the BRIEF questionnaire. BC exposures in the birth-age 3 period and the third trimester of pregnancy were not associated with worse teacher-rated BRIEF scores, and BC exposure in the fourth, fifth, and sixth years of life appeared more strongly associated with teacher-rated BRIEF BRI scores than exposure in the first, second, and third years, suggesting that mid-childhood exposure may have a greater adverse effect than prenatal or early childhood exposure on executive function at ages 6-10. These results may also indicate that the observed associations are related to cumulative BC exposure throughout early life; high correlations of BC exposure in the year prior to behavioral ratings with birth-age 3 BC exposure (Spearman r=0.81) and birth-age 6 BC exposure (Spearman r=0.88) limit our ability to fully isolate the effects of exposure in later versus earlier childhood.

Childhood BC exposure did not appear associated with the Metacognition Index of the BRIEF (which measures "higher level" executive functions related to planning and problem solving) (Gioia et al. 2002), indicating that the BRIEF Behavior Regulation Index may be a more sensitive measure of the neurodevelopmental effects of childhood exposure to traffic-related pollution than the Metacognition Index among children in the studied age range (6-10 years).

The observed results are consistent with findings in another Boston cohort (aged 7-14 years) that childhood BC exposure (average since birth) was associated with errors of commission on the Connors' Continuous Performance Test, suggesting poorer inhibitory control; BC exposure also predicted slower reaction time in that cohort (Chiu et al. 2013). Our findings are also broadly similar to those of previous studies that have observed greater neurobehavioral problems among children with higher childhood exposure to traffic-related pollution, although direct comparability is limited because these studies employed different outcome assessments and exposure measures (Forns et al. 2015; Sunyer et al. 2015; Newman et al. 2013; Siddique et al. 2011; Wang et al. 2009). While earlier studies in New York City reported associations between prenatal PAH exposure and neurobehavioral problems (anxiety/depression behaviors at ages 6-7 and greater ADHD-related behaviors at age 9) (Perera et al. 2012; Perera et al. 2014), prenatal exposure to BC in our cohort did not predict worse outcomes (in fact, teacher-rated metacognition was somewhat better among children with higher prenatal BC exposure, although this is an association that we do not believe has a plausible casual explanation). In general, differences between our findings and those from New York City may relate to differences in sources and exposure levels of pollution in New York versus Boston, differences in mechanism of effect of PAH versus BC, differences in the precision of exposure estimates, or differences in susceptibility of the study populations.

Multiple mechanisms may underlie the associations we observed between childhood exposure to traffic-related air pollution and behavior regulation problems. Systemic inflammatory responses or ultrafine particles that reach the brain may trigger neuroinflammation leading to brain damage through oxidative stress; pollution components including metals, solvents, and PAHs may also be directly neurotoxic (Block et al. 2012). In contrast to some brain regions that are more highly developed at birth, the prefrontal cortex,

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a region thought to be important in facilitating behavioral regulation through inhibitory control, undergoes substantial and critical development throughout childhood and adolescence (Casey et al. 2000; Tsujimoto 2008).

Evidence suggests that the prefrontal cortex may be a particularly sensitive target for neurological effects of air pollution exposure. Children exposed to high levels of urban air pollution in Mexico City had white matter lesions in the prefrontal cortex that were not seen in Mexican children with lower air pollution exposure (Calderon-Garciduenas et al. 2008). Dogs exposed to Mexico City air pollution displayed similar white matter lesions, along with increased neuroinflammation in frontal white matter compared to control dogs, and deposits of ultrafine particles in frontal blood vessels (Calderon-Garciduenas et al. 2008). Higher PAH exposure at age 5 in New York City children was associated with reduced surface white matter in the dorsal prefrontal regions at mean age 8 (while prenatal PAH exposure was independently associated with reductions in white matter surfaces throughout the left hemisphere of the brain) (Peterson et al. 2015). Among 8-12 year old children in Barcelona, childhood exposure to traffic-related air pollution was associated with differences in functional connectivity of neural networks involving the medial frontal cortex; these patterns of functional connectivity were opposite to those associated with increased age and faster reaction time, suggesting that childhood exposure to air pollution was associated with slower brain maturation (Pujol et al. 2016). Adult volunteers given experimental short-term exposures to diesel exhaust displayed changes in frontal cortex brain activity, suggesting a stress response in that region of the brain (Cruts et al. 2008). Mice experimentally exposed to ultrafine particles (aerodynamic diameter <100 nm) at environmentally-relevant concentrations in the postnatal period showed greater preference for immediate reward, which may be an indicator of impulsivity (Allen et al. 2013); exposed mice were also observed to have alterations in neurotransmitter levels, including increased glutamate in the frontal cortex, which investigators postulated could indicate an excitotoxic mechanism of particulate air pollution in the brain (Allen et al. 2014).

In contrast to our findings for teacher-rated BRIEF scores, in linear models parent-rated BRIEF scores were not associated with childhood BC exposure and third trimester BC exposure predicted slightly better parent-rated BRIEF GEC scores. Parent and teacher ratings assess behaviors in different environments. The discrepancy between results for parent- and teacher-rated questionnaires may indicate that subtle, sub-clinical executive functioning problems may be more apparent in a school setting rather than at home. We observed only moderate inter-rater correlation between parent and teacher rating scale scores in our study population, which is consistent with patterns observed by other researchers and in normative population samples (Gioia et al. 2000; Mares et al. 2007).

None of the traffic-related exposures we examined predicted worse parent- or teacher-rated SDQ total difficulties scores in covariate-adjusted linear models. The SDQ is a relatively short questionnaire, and while it has been shown to have good validity as a primary screening instrument for childhood psychosocial disorders (Stone et al. 2010), its usefulness in assessing subtle effects in community populations has been less well-studied.

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Our data suggested that associations between childhood BC exposure and teacher- and parent-rated BRIEF and SDQ scores were not linear. Below a mean exposure of 0.5 $\mu g/m^3$, higher BC exposure in the year prior to behavioral ratings appeared to have no effect (or a slightly beneficial effect) on parent- and teacher-rated BRIEF and SDQ scores, whereas above 0.5 $\mu g/m^3$, higher exposure generally predicted worse scores. This observed non-linearity may suggest a concentration threshold around 0.5 $\mu g/m^3$ below which childhood exposure to BC has less harmful influence on child executive function and behavior. It is also possible that non-linearity could stem from residual confounding or effect modification by factors that differ between participants with higher and lower BC exposure.

In our study population, BC exposure was higher, on average, among black and Hispanic participants compared to white and Asian participants. Participants with higher exposure to BC tended to have lower household income and live in neighborhoods with lower median annual household income. These findings are consistent with prior evidence that exposures to ambient traffic-related air pollution in urban areas are higher among racial and ethnic minority populations and in lower income communities (Hajat et al. 2013; Jerrett 2009; Jones et al. 2014). We adjusted for potential confounding by race, household income, neighborhood income, and other factors in our primary models, but influences of traffic-related pollutants and socioeconomic factors may be challenging to fully differentiate in this population, and it is possible that residual confounding may fully or partially explain the associations we observed.

Through correlated with BC exposure, childhood $PM_{2.5}$ exposure was a weaker predictor of teacher-rated BRIEF scores than childhood BC exposure. Although $PM_{2.5}$ is emitted by vehicles, it also has many non-traffic sources, meaning $PM_{2.5}$ is considered a less specific marker of traffic-related pollution than BC (Karner et al. 2010). Our results have similarities to those of a study of Barcelona school-children, in which total $PM_{2.5}$ measured in classrooms was not associated with measures of cognitive development but higher exposure to the portion of $PM_{2.5}$ mass attributable to traffic (determined through source apportionment) was associated with slower improvements in attentiveness and working memory over the study period (Basagaña et al. 2016). In our study, near-residence traffic density at mid-childhood address, which we employed as a proxy measure of childhood exposure to traffic-related pollution, was also associated with a smaller increase in teacher-rated BRIEF scores than childhood BC exposure, suggesting that BC may be a relatively more harmful component of the mix of pollutants related to traffic.

We observed suggestive evidence that closer proximity to major roadways at mid-childhood might be associated with worse teacher-rated BRIEF BRI scores. Teachers also rated children living within 50 meters of a major roadway at birth as having more executive function and behavior problems on average (higher BRIEF and SDQ scores), but the small number of children in this category (n=34) limited the precision of effect estimates. This pattern reflects earlier findings in the Project Viva cohort suggesting that children with birth addresses <50 meters from a major roadway had lower non-verbal intelligence, verbal intelligence and visual motor abilities in mid-childhood (although precision was also limited in that study) (Harris et al. 2015). In contrast, parent-rated BRIEF scores were lower, indicating fewer problems, for children living <50 meters from a major roadway at birth. It

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seems unlikely that this association is causal; it may be attributable to confounding we were unable to account for in our analyses, or may be a chance association.

Additional limitations of our analyses should be noted. We assessed executive function and behavior based on validated rating scales completed by teachers and parents, but did not have access to performance-based tests of specific neurobehavioral functions such as attention or inhibitory control. Rating scales and neurobehavioral tests are complementary measures ideally used in combination to assess neurobehavioral development; while rating scales have the advantage of evaluating behavior in everyday life, they may assess different underlying mental constructs than performance-based measures (Toplak et al. 2013). Additional measures might have allowed us to identify effects of air pollution exposure on childhood neurobehavior that could not be identified through observer responses to behavioral rating scales. In addition, because executive function develops throughout childhood and adolescence (Anderson 2002), the behavioral rating scales conducted in the study population at ages 6-10 may not have captured potential effects of air pollution exposure on aspects of executive function that are better solidified later in development (or those relevant primarily at younger ages). The association of air pollution exposure with neurobehavioral development should be further explored in studies employing combined batteries of multi-informant rating scales and performance-based neuropsychological tests conducted longitudinally at multiple points in childhood and adolescence.

Although our primary models were adjusted for maternal IQ, we lacked other measures of parental neurobehavior (e.g., executive function). Exposure estimates were based on residential addresses and time-activity data were not available, so exposure measures did not incorporate exposure outside the home and were therefore certainly misclassified to some degree (Lane et al. 2013). Median census tract household income, which we used as a covariate representing neighborhood socioeconomic characteristics, was drawn from year 2000 census data, so this variable may have been misclassified if neighborhood characteristics changed substantially between the 2000 census and the mid-childhood study visits (conducted in 2007-2011). Primarily as a result of loss to follow-up soon after birth in Project Viva, our study included only a subset (57%) of participants originally enrolled in early pregnancy. While prenatal traffic-related pollution exposures appeared similar for excluded and included participants, some demographic characteristics and health-related behaviors differed between excluded and included participants, so selection bias is a possibility. Lastly, although the study cohort included participants with a range of racial/ethnic backgrounds and income levels, enrolled mothers all had health insurance coverage and access to early prenatal care and were on average highly educated and higher income, which may limit the applicability of findings to less advantaged populations.

Our study also had a number of strengths. We assessed multiple measures of traffic-related pollution exposure and multiple developmental windows in an effort to investigate influential pollution components and sensitive exposure periods in relation to childhood executive function and behavior. We used multiple behavioral rating scales completed by informants in multiple settings (classroom teachers and parents). We were able to examine and adjust for a broad range of potential confounding variables, including co-exposures previously observed to influence neurodevelopment and multiple measures of household- and area-level socioeconomic status.

Our results add to a growing literature suggesting that exposure to traffic-related pollution may contribute to neurobehavioral problems in children. Given the ubiquity of traffic exposure in urban and suburban areas, potential adverse impacts to neurodevelopment represent a serious public health concern, and interventions to limit exposure of children to traffic-related pollution are warranted.

5. Conclusions

Children with higher childhood exposure to BC had greater problems with behavioral regulation as assessed by classroom teachers (but not as assessed by parents), and evidence suggested that mid-childhood might be a more sensitive exposure period than early childhood or gestation for negative effects of BC exposure on executive function measured at 6-10 years. We observed evidence of non-linearity in relationships between childhood BC exposure and rating scales of executive function, which might indicate a potential threshold for adverse neurodevelopmental effects around 0.5 $\mu g/m^3$ ambient BC concentration. Childhood BC exposure appeared to be more strongly predictive of teacher-rated executive function problems than $PM_{2.5}$ exposure, near-residence traffic density, or residential proximity to major roadway. Our results suggest that childhood exposure to traffic-related pollution may adversely affect executive function development. Together with prior literature reporting adverse neurodevelopmental effects of traffic exposure, these findings provide support for public health interventions to reduce exposure to traffic-related pollution among children.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- We studied early life exposure to traffic-related air pollution and child behavior.
- Exposure to ambient black carbon predicted worse behavioral regulation ratings.
- Childhood black carbon exposure appeared more influential than prenatal exposure.
- Other traffic exposure measures were less strongly associated with behavioral scores.

Table 1

Characteristics of study participants overall and by childhood BC exposure

	All participants[a] (n=1,212)		Participants with mean BC exposure in year prior to behavioral ratings ≤ 0.5 μg/m^3 (n=614)	Participants with mean BC exposure in year prior to behavioral ratings > 0.5 μg/m^3 (n=395)
	N	**Mean ± SD or %**		
Behavioral Rating Scales				
Teacher-rated BRIEF Global Executive Composite (GEC) score[b]	878	51.0 ± 10.5	49.5 ± 8.7	54.0 ± 12.5
Teacher-rated BRIEF Behavior Regulation Index (BRI) score[b]	878	50.8 ± 10.1	49.1 ± 7.7	53.9 ± 12.7
Teacher-rated BRIEF Metacognition Index (MI) score[b]	878	51.1 ± 10.7	49.9 ± 9.5	53.6 ± 12.2
Teacher-rated SDQ Total Difficulties score[c]	901	6.4 ± 5.9	5.9 ± 5.3	7.5 ± 6.6
Parent-rated BRIEF GEC score[b]	1,172	48.7 ± 9.2	48.5 ± 9.2	49.0 ± 9.1
Parent-rated BRIEF BRI score[b]	1,172	48.2 ± 8.8	48.0 ± 8.8	48.6 ± 8.9
Parent-rated BRIEF MI score[b]	1,172	48.4 ± 8.7	48.3 ± 8.8	48.7 ± 8.9
Parent-rated SDQ Total Difficulties score[c]	1,189	6.6 ± 4.8	6.2 ± 4.6	7.2 ± 4.9
Child characteristics				
Age when teacher completed behavioral rating scales (years)	903	8.1 ± 0.8	8.0 ± 0.8	8.1 ± 0.9
Age when parent completed behavioral rating scales (years)	1,195	7.9 ± 0.8	7.9 ± 0.7	8.0 ± 0.9
Sex	1,212			
Female (%)	608	50	51	50
Male (%)	604	50	49	50
Gestational age (weeks)	1,212	39.5 ± 1.8	39.6 ± 1.7	39.5 ± 1.9
Birth weight (grams)	1,212	3,485 ± 555	3,532 ± 536	3,417 ± 581
Birth weight/gestational age z-score	1,212	0.19 ± 0.96	0.27 ± 0.95	0.06 ± 0.98
Duration of breastfeeding (months up to 12)	1,212	6.3 ± 4.8	6.2 ± 4.7	6.0 ± 4.9

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	All participants[a] (n=1,212)		Participants with mean BC exposure in year prior to behavioral ratings ≤ 0.5 μg/m^3 (n=614)	Participants with mean BC exposure in year prior to behavioral ratings > 0.5 μg/m^3 (n=395)
	N	**Mean ± SD or %**		
Early childhood blood lead (μg/dL)	1,212	2.3 ± 2.2	2.2 ± 1.9	2.5 ± 2.0
Maternal characteristics				
Age at enrollment (years)	1,212	32.2 ± 5.2	32.6 ± 4.6	31.3 ± 6.3
IQ (KBIT-2 composite)	1,212	106.6 ± 15.7	108.5 ± 14.5	102.6 ± 16.3
Parity	1,212			
Nulliparous (%)	584	48	46	45
1 (%)	434	36	39	35
≥2 (%)	194	16	15	20
Education	1,212			
College degree or beyond (%)	836	69	75	55
Less than college degree (%)	376	31	25	45
Race/ethnicity	1,212			
White (%)	834	69	81	50
Black (%)	182	15	8	28
Asian (%)	66	5	6	4
Hispanic (%)	76	6	4	11
Other (%)	53	4	2	7
Alcohol consumption during pregnancy (g/day)	1,212	0.18 ± 0.26	0.19 ± 0.25	0.16 ± 0.26
Smoking status	1,212			
Smoked during pregnancy (%)	117	10	10	11
Former smoker (%)	232	19	19	17
Never smoker (%)	863	71	71	72
Exposure to secondhand smoke during pregnancy	1,212			
≥1 hour per week (%)	207	17	15	22
<1 hour per week (%)	1,005	83	85	78
Marital/cohabitation status	1,212			

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	All participants[a] (n=1,212)		Participants with mean BC exposure in year prior to behavioral ratings ≤ 0.5 μg/m^3 (n=614)	Participants with mean BC exposure in year prior to behavioral ratings > 0.5 μg/m^3 (n=395)
	N	Mean ± SD or %		
Married or cohabitating (%)	1,113	92	96	84
Not married or cohabitating (%)	99	8	4	16
Blood lead in pregnancy (μg/dL)	1,212	1.3 ± 0.8	1.2 ± 0.7	1.3 ± 0.9
Paternal characteristics				
Education	1,212			
College degree or beyond (%)	780	64	70	48
Less than college degree (%)	431	36	30	52
Household/neighborhood characteristics				
Household income at mid-childhood	1,212			
<$40K (%)	145	12	7	21
$40-70K (%)	172	14	10	19
$70-150K (%)	552	46	49	39
>$150 K (%)	343	28	34	20
HOME-SF score[d]	1,212	18.3 ± 2.2	18.6 ± 2.1	17.9 ± 2.4
Gas stove in home at age 1	1,212			
Yes (%)	703	58	50	72
No (%)	509	42	50	28
Census tract median annual household income, mid-childhood address ($)	1,212	65,311 ± 25,205	73,580 ± 22,817	51,664 ± 19,978

[a]Includes participants with multiply imputed covariates.

[b]Behavior Rating Inventory of Executive Function (BRIEF) Index and Composite scores standardized to mean=50, standard deviation=10 with higher scores representing greater executive function problems. BRIEF Global Executive Composite score combines Metacognition Index and Behavior Regulation Index scores.

[c]Strengths and Difficulties Questionnaire (SDQ) Total Difficulties scores have possible values of 0-40 with higher scores representing greater behavioral problems.

[d]The HOME-SF, or Home Observation for Measurement of the Environment (Short Form) assessment, used to measure emotional support and cognitive stimulation in the child's home; Scale: 0-22, with higher scores representing greater support.

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Table 2

Traffic-related pollution exposures and relation to BC exposure in year prior to behavioral ratings

	N	Mean ± SD	Correlation with mean BC exposure in year prior to behavioral ratings (Spearman *r*)[a]
Black carbon (BC) exposure			
Third trimester (μg/m^3)	1197	0.69 ± 0.23	0.58
Birth– age 3 (μg/m^3)	1069	0.61 ± 0.17	0.81
Birth– age 6 (μg/m^3)	992	0.56 ± 0.16	0.88
Year prior to behavioral ratings (μg/m^3)	1009	0.47 ± 0.14	-
Fine particulate ($PM_{2.5}$) exposure			
Third trimester (μg/m^3)	1046	12.3 ± 2.5	0.32
Birth– age 3 (μg/m^3)	1082	12.0 ± 1.8	0.49
Birth– age 6 (μg/m^3)	1023	11.3 ± 1.7	0.54
Year prior to behavioral ratings (μg/m^3)	1084	9.4 ± 1.9	0.44
Near-residence traffic density			
Birth address (km*vehicles/day)	1203	1,425 ± 1,813	0.40
Mid-childhood address (km*vehicles/day)	1035	1,130 ± 1,598	0.65
	N	**N (%)**	**BC exposure in year prior to behavioral assessment exposure by category (μg/m^3) (Mean ± SD)**
Proximity to major roadway, birth address	1207		
<50 m		34 (3%)	0.53 ± 0.18
50– <200 m		108 (9%)	0.52 ± 0.16
≥200 m		1065 (88%)	0.46 ± 0.14
Proximity to major roadway, mid-childhood address	1198		
<50 m		27 (2%)	0.56 ± 0.15
50– <200 m		93 (8%)	0.56 ± 0.16
≥200 m		1078 (90%)	0.46 ± 0.14

SD, standard deviation.

[a]All Spearman correlation coefficient p-values <.0001

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Table 3

Linear model results for mean difference in teacher-rated executive function and behavior problems associated with residential major roadway proximity and interquartile range increases in exposure to traffic density, black carbon, and fine particulate matter (+ 95% confidence intervals) among 1,212 Project Viva children

	Model 0 (adjusted for child age and sex)[a]				Model 1 (covariate-adjusted)[b]			
	BRIEF Global Executive Composite (GEC)	BRIEF Behavioral Regulation Index (BRI)	BRIEF Metacognition Index (MI)	SDQ Total Difficulties	BRIEF Global Executive Composite (GEC)	BRIEF Behavioral Regulation Index (BRI)	BRIEF Metacognition Index (MI)	SDQ Total Difficulties
Black carbon (BC) exposure								
Third trimester	0.6 (−0.4, 1.5)	1.2 (0.3, 2.2)	0.2 (−0.8, 1.1)	−0.1 (−0.6, 0.4)	−1.0 (−1.9, 0.0)	−0.2 (−1.1, 0.8)	−1.2 (−2.2, −0.2)	−0.9 (−1.4, −0.4)
Birth– age 3	1.9 (1.0, 2.8)	2.3 (1.4, 3.2)	1.5 (0.6, 2.5)	0.7 (0.2, 1.2)	0.0 (−1.0, 1.0)	0.6 (−0.4, 1.5)	−0.3 (−1.4, 0.7)	−0.3 (−0.9, 0.2)
Birth– age 6	2.3 (1.3, 3.2)	2.7 (1.8, 3.7)	1.8 (0.8, 2.8)	0.9 (0.3, 1.4)	0.4 (−0.7, 1.5)	1.0 (0.0, 2.1)	0.0 (−1.1, 1.2)	−0.1 (−0.7, 0.5)
Year before behavioral ratings	2.7 (1.8, 3.7)	3.2 (2.3, 4.1)	2.1 (1.2, 3.1)	1.1 (0.6, 1.7)	1.0 (−0.1, 2.1)	1.7 (0.6, 2.8)	0.5 (−0.6, 1.6)	0.1 (−0.5, 0.8)
Fine particulate ($PM_{2.5}$) exposure								
Third trimester	0.9 (−0.1, 2.0)	1.3 (0.3, 2.4)	0.7 (−0.4, 1.8)	0.3 (−0.3, 0.9)	−0.1 (−1.2, 0.9)	0.2 (−0.8, 1.3)	−0.3 (−1.4, 0.8)	−0.3 (−0.9, 0.3)
Birth– age 3	1.7 (0.9, 2.6)	1.8 (1.0, 2.6)	1.5 (0.6, 2.4)	0.8 (0.3, 1.3)	0.3 (−0.6, 1.2)	0.4 (−0.5, 1.3)	0.2 (−0.7, 1.1)	0.1 (−0.4, 0.6)
Birth– age 6	1.9 (1.1, 2.8)	2.1 (1.2, 2.9)	1.6 (0.7, 2.5)	0.9 (0.4, 1.4)	0.5 (−0.5, 1.4)	0.7 (−0.2, 1.6)	0.3 (−0.7, 1.3)	0.1 (−0.4, 0.6)
Year before behavioral ratings	1.3 (0.3, 2.2)	1.3 (0.3, 2.2)	1.1 (0.1, 2.1)	0.6 (0.1, 1.2)	0.2 (−0.8, 1.1)	0.1 (−0.8, 1.1)	0.1 (−0.9, 1.1)	0.1 (−0.5, 0.6)
Near-residence traffic density								
Birth address	0.1 (−0.4, 0.6)	0.4 (−0.1, 0.9)	0.0 (−0.5, 0.5)	0.1 (−0.2, 0.4)	−0.1 (−0.6, 0.4)	0.1 (−0.4, 0.6)	−0.2 (−0.7, 0.3)	0.0 (−0.3, 0.3)
Mid-childhood address	0.8 (0.3, 1.4)	1.2 (0.7, 1.7)	0.5 (0.0, 1.1)	0.3 (0.0, 0.6)	0.2 (−0.3, 0.8)	0.6 (0.1, 1.1)	0.0 (−0.5, 0.5)	0.1 (−0.2, 0.3)
Proximity to major roadway, birth address								
<50 m	2.9 (−1.5, 7.4)	3.8 (−0.7, 8.2)	2.0 (−2.5, 6.6)	1.1 (−1.4, 3.7)	2.7 (−1.6, 7.1)	3.5 (−0.7, 7.8)	1.8 (−2.6, 6.3)	1.5 (−1.0, 3.9)

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	Model 0 (adjusted for child age and sex)[a]				Model 1 (covariate-adjusted)[b]			
	BRIEF Global Executive Composite (GEC)	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**	**BRIEF Global Executive Composite (GEC)**	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**
50– <200 m	−1.0 (−3.4, 1.4)	−0.1 (−2.5, 2.3)	−1.5 (−3.9, 1.0)	0.2 (−1.2, 1.5)	−1.3 (−3.6, 0.9)	−0.6 (−2.8, 1.7)	−1.7 (−4.0, 0.7)	0.0 (−1.3, 1.3)
≥200 m	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)
Proximity to major roadway, mid-childhood address								
<50 m	3.5 (−1.0, 8.0)	4.6 (0.1, 9.0)	2.5 (−2.1, 7.1)	1.3 (−1.2, 3.8)	1.2 (−3.1, 5.5)	2.0 (−2.2, 6.3)	0.5 (−3.9, 5.0)	0.1 (−2.4, 2.5)
50– <200 m	1.6 (−0.9, 4.0)	2.0 (−0.4, 4.5)	1.1 (−1.4, 3.6)	0.9 (−0.5, 2.3)	0.3 (−2.1, 2.6)	0.5 (−1.8, 2.9)	0.0 (−2.4, 2.5)	0.1 (−1.3, 1.4)
≥200 m	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)

BRIEF is Behavioral Rating Inventory of Executive Function; BRIEF scores standardized to mean=50, standard deviation=10 with higher scores representing greater executive function problems. SDQ is Strengths and Difficulties Questionnaire; SDQ total difficulties scores have possible values of 0-40 with higher scores representing greater behavioral problems Interquartile range= 1,425 km*vehicles/day for traffic density at birth, 1,241 km*vehicles/day for mid-childhood traffic density, 0.33 μg/m^3 for third trimester BC, 0.23 μg/m^3 for birth-age 3 BC, 0.22 μg/m^3 for birth-age 6 BC, 0.20 μg/m^3 for BC in year before behavioral ratings, 3.8 μg/m^3 for third trimester $PM_{2.5}$, 2.2 μg/m^3 for birth-age 3 $PM_{2.5}$, 2.1 μg/m^3 for birth-age 6 $PM_{2.5}$, 2.5 μg/m^3 for $PM_{2.5}$ in year before behavioral ratings.

[a]Model 0 adjusted for of child age at behavioral ratings and sex. Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.

[b]Model 1 adjusted for characteristics of child (age, sex, breastfeeding duration, early childhood blood lead), mother (age, parity, race/ethnicity, education, IQ, marital/cohabitation status, and blood lead, smoking, secondhand smoke exposure, and alcohol in pregnancy), father (education), household (income, home caretaking environment, gas stove) and neighborhood (census tract median income). Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.

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Table 4

Piecewise linear model results for mean difference in teacher-rated Behavior Rating Inventory of Executive Function (BRIEF) scores associated with 0.2 $\mu g/m^3$ increase in exposure to black carbon (+ 95% confidence intervals) above and below mean exposure of 0.5 $\mu g/m^3$ black carbon (BC)[a]

	≤ 0.5 $\mu g/m^3$ BC				> 0.5 $\mu g/m^3$ BC			
	BRIEF Global Executive Composite (GEC)	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**	**BRIEF Global Executive Composite (GEC)**	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**
Third trimester BC	−2.3 (−4.6, 0.1)	−1.5 (−3.8, 0.8)	−2.3 (−4.7, 0.2)	−1.1 (−2.4, 0.3)	2.0 (−0.7, 4.7)	1.7 (−1.0, 4.3)	1.8 (−1.0, 4.6)	0.6 (−0.9, 2.2)
Birth– age 3 BC	−1.4 (−3.8, 1.1)	−1.5 (−3.8, 0.9)	−0.9 (−3.5, 1.6)	−0.9 (−2.3, 0.5)	1.8 (−1.3, 4.9)	2.6 (−0.4, 5.6)	0.9 (−2.3, 4.1)	0.8 (−0.9, 2.6)
Birth– age 6 BC	−1.8 (−4.1, 0.5)	−1.7 (−4.0, 0.5)	−1.4 (−3.8, 0.9)	−0.9 (−2.2, 0.4)	3.3 (0.2, 6.4)	4.1 (1.1, 7.1)	2.3 (−1.0, 5.5)	1.2 (−0.6, 3.0)
Year before behavioral ratings BC	−0.9 (−2.8, 1.0)	−0.6 (−2.5, 1.2)	−0.9 (−2.9, 1.0)	−0.8 (−1.9, 0.3)	3.9 (0.8, 7.1)	4.8 (1.7, 7.8)	2.9 (−0.3, 6.2)	2.0 (0.2, 3.7)

[a] All models adjusted for characteristics of child (age, sex, breastfeeding duration, early childhood blood lead), mother (age, parity, race/ethnicity, education, IQ, marital/cohabitation status, and blood lead, smoking, secondhand smoke exposure, and alcohol in pregnancy), father (education), household (income, home caretaking environment, gas stove) and neighborhood (census tract median income). Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.

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Table 5

Linear model results for mean difference in parent-rated executive function and behavior problems associated with residential major roadway proximity and interquartile range increases in exposure to traffic density, black carbon, and fine particulate matter (+ 95% confidence intervals)

	Model 0 (adjusted for child age and sex)[a]				Model 1 (covariate-adjusted)[b]			
	BRIEF Global Executive Composite (GEC)	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**	**BRIEF Global Executive Composite (GEC)**	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**
Black carbon (BC) exposure								
Third trimester	−0.1 (−0.8, 0.7)	0.2 (−0.5, 0.9)	−0.1 (−0.8, 0.7)	0.4 (0.0, 0.7)	−0.9 (−1.6, −0.1)	−0.6 (−1.4, 0.1)	−0.8 (−1.5, 0.0)	−0.2 (−0.6, 0.2)
Birth– age 3	0.4 (−0.3, 1.2)	0.4 (−0.3, 1.2)	0.4 (−0.3, 1.1)	0.6 (0.2, 1.0)	−0.5 (−1.3, 0.4)	−0.5 (−1.3, 0.3)	−0.3 (−1.1, 0.5)	−0.1 (−0.5, 0.3)
Birth– age 6	0.6 (−0.1, 1.4)	0.7 (−0.1, 1.4)	0.6 (−0.2, 1.3)	0.7 (0.3, 1.1)	−0.3 (−1.2, 0.6)	−0.3 (−1.2, 0.6)	−0.1 (−1.0, 0.7)	0.0 (−0.5, 0.4)
Year before behavioral ratings	0.7 (−0.1, 1.4)	0.7 (−0.1, 1.4)	0.6 (−0.2, 1.3)	0.7 (0.3, 1.1)	−0.1 (−1.0, 0.8)	−0.2 (−1.1, 0.7)	0.1 (−0.8, 0.9)	0.1 (−0.4, 0.5)
Fine particulate ($PM_{2.5}$) exposure								
Third trimester	0.0 (−0.8, 0.9)	0.6 (−0.2, 1.4)	−0.2 (−1.0, 0.6)	0.1 (−0.4, 0.5)	−0.5 (−1.3, 0.4)	0.1 (−0.7, 1.0)	−0.7 (−1.5, 0.2)	−0.3 (−0.7, 0.1)
Birth– age 3	0.6 (0.0, 1.3)	0.8 (0.2, 1.5)	0.4 (−0.2, 1.1)	0.4 (0.1, 0.8)	0.0 (−0.7, 0.7)	0.2 (−0.5, 0.9)	−0.1 (−0.8, 0.6)	0.0 (−0.4, 0.3)
Birth– age 6	0.5 (−0.1, 1.2)	0.7 (0.1, 1.4)	0.4 (−0.3, 1.0)	0.5 (0.1, 0.8)	−0.2 (−0.9, 0.5)	0.0 (−0.7, 0.7)	−0.3 (−1.0, 0.5)	−0.1 (−0.5, 0.3)
Year before behavioral ratings	0.2 (−0.5, 1.0)	0.4 (−0.3, 1.1)	0.1 (−0.6, 0.8)	0.3 (−0.1, 0.7)	−0.2 (−0.9, 0.6)	0.0 (−0.8, 0.7)	−0.2 (−1.0, 0.5)	−0.1 (−0.5, 0.3)
Near-residence traffic density								
Birth address	0.1 (−0.4, 0.6)	0.0 (−0.4, 0.4)	0.1 (−0.2, 0.5)	0.1 (−0.1, 0.4)	−0.1 (−0.5, 0.3)	−0.1 (−0.5, 0.3)	0.0 (−0.4, 0.4)	0.1 (−0.1, 0.3)
Mid-childhood address	0.2 (−0.2, 0.7)	0.4 (0.0, 0.9)	0.1 (−0.4, 0.5)	0.3 (0.1, 0.6)	0.0 (−0.5, 0.4)	0.2 (−0.2, 0.6)	−0.2 (−0.6, 0.3)	0.1 (−0.1, 0.3)
Proximity to major roadway, birth address								
<50 m	−0.2 (−3.4, 3.0)	0.3 (−2.8, 3.3)	0.0 (−3.1, 3.0)	0.9 (−0.7, 2.6)	0.2 (−2.9, 3.4)	0.4 (−2.6, 3.5)	0.5 (−2.5, 3.5)	0.9 (−0.6, 2.5)

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	Model 0 (adjusted for child age and sex)[a]				Model 1 (covariate-adjusted)[b]			
	BRIEF Global Executive Composite (GEC)	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**	**BRIEF Global Executive Composite (GEC)**	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**
50– <200 m	0.1 (−1.7, 1.9)	1.2 (−0.5, 3.0)	−0.4 (−2.1, 1.3)	−0.1 (−1.1, 0.8)	0.0 (−1.8, 1.8)	1.1 (−0.7, 2.8)	−0.5 (−2.2, 1.2)	−0.3 (−1.2, 0.6)
≥200 m	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)
Proximity to major roadway, mid-childhood address								
<50 m	−2.5 (−6.1, 1.1)	−1.9 (−5.4, 1.6)	−2.4 (−5.9, 1.1)	0.7 (−1.2, 2.6)	−3.6 (−7.1, −0.1)	−3.2 (−6.7, 0.2)	−3.1 (−6.5, 0.3)	−0.3 (−2.1, 1.5)
50– <200 m	0.6 (−1.4, 2.5)	1.3 (−0.5, 3.2)	−0.2 (−2.0, 1.6)	0.0 (−1.0, 1.0)	0.2 (−1.7, 2.1)	0.9 (−0.9, 2.8)	−0.5 (−2.3, 1.3)	−0.4 (−1.3, 0.6)
≥200 m	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)	0.0 (Ref)

BRIEF is Behavioral Rating Inventory of Executive Function; BRIEF scores standardized to mean=50, standard deviation=10 with higher scores representing greater executive function problems. SDQ is Strengths and Difficulties Questionnaire; SDQ total difficulties scores have possible values of 0-40 with higher scores representing greater behavioral problems Interquartile range= 1,425 km*vehicles/day for traffic density at birth, 1,241 km*vehicles/day for mid-childhood traffic density, 0.33 μg/m^3 for third trimester BC, 0.23 μg/m^3 for birth-age 3 BC, 0.22 μg/m^3 for birth-age 6 BC, 0.20 μg/m^3 for BC in year before behavioral ratings, 3.8 μg/m^3 for third trimester $PM_{2.5}$, 2.2 μg/m^3 for birth-age 3 $PM_{2.5}$, 2.1 μg/m^3 for birth-age 6 $PM_{2.5}$, 2.5 μg/m^3 for $PM_{2.5}$ inyear before behavioralratings.

[a] Model 0 adjusted for of child age at behavioral ratings and sex. Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.

[b] Model 1 adjusted for characteristics of child (age, sex, breastfeeding duration, early childhood blood lead), mother (age, parity, race/ethnicity, education, IQ, marital/cohabitation status, and blood lead, smoking, secondhand smoke exposure, and alcohol in pregnancy), father (education), household (income, home caretaking environment, gas stove) and neighborhood (census tract median income). Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.

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Table 6

Piecewise linear model results for mean difference in parent-rated Behavior Rating Inventory of Executive Function (BRIEF) scores associated with 0.2 μg/m^3 increase in exposure to black carbon (+ 95% confidence intervals) above and below mean exposure of 0.5 μg/m^3 black carbon (BC)[a]

	≤ 0.5 μg/m^3 BC				> 0.5 μg/m^3 BC			
	BRIEF Global Executive Composite (GEC)	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**	**BRIEF Global Executive Composite (GEC)**	**BRIEF Behavioral Regulation Index (BRI)**	**BRIEF Metacognition Index (MI)**	**SDQ Total Difficulties**
Third trimester BC	−0.9 (−2.8, 1.0)	−0.5 (−2.4, 1.4)	−0.7 (−2.6, 1.1)	0.4 (−0.6, 1.3)	0.4 (−1.8, 2.7)	0.1 (−2.0, 2.3)	0.3 (−1.8, 2.4)	−0.6 (−1.7, 0.5)
Birth– age 3 BC	−0.5 (−2.5, 1.6)	−0.4 (−2.4, 1.6)	−0.1 (−2.1, 1.8)	0.7 (−0.4, 1.7)	0.1 (−2.5, 2.7)	−0.1 (−2.6, 2.5)	−0.1 (−2.6, 2.3)	−1.0 (−2.3, 0.3)
Birth– age 6 BC	−0.5 (−2.4, 1.4)	−0.5 (−2.4, 1.3)	−0.2 (−2.0, 1.7)	0.5 (−0.4, 1.5)	0.3 (−2.3, 2.9)	0.4 (−2.2, 2.9)	0.1 (−2.4, 2.6)	−0.8 (−2.1, 0.5)
Year before behavioral ratings BC	−1.4 (−2.9, 0.2)	−1.4 (−2.9, 0.1)	−1.0 (−2.5, 0.5)	−0.3 (−1.1, 0.5)	2.7 (0.1, 5.3)	2.5 (0.0, 5.1)	2.2 (−0.3, 4.6)	0.7 (−0.6, 2.0)

[a] All models adjusted for characteristics of child (age, sex, breastfeeding duration, early childhood blood lead), mother (age, parity, race/ethnicity, education, IQ, marital/cohabitation status, and blood lead, smoking, secondhand smoke exposure, and alcohol in pregnancy), father (education), household (income, home caretaking environment, gas stove) and neighborhood (census tract median income). Third trimester BC and $PM_{2.5}$ models also adjusted for seasonal trends.