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Combined association of BTEX and material hardship on ADHD-suggestive behaviours among a nationally representative sample of US children

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Abstract

Background: Previous research shows that environmental and social factors contribute to the development of attention-deficit/hyperactivity disorder (ADHD).

Objective: To determine the relationship between early-life exposure to common ambient air pollutants (benzene, toluene, ethylbenzene, and xylene, also known as BTEX), household material hardship (a measure of socio-economic status), and ADHD-suggestive behaviours in kindergarten-age children.

Methods: Pollutant exposure estimated from the 2002 National Air Toxics Assessment at each child's residential ZIP code at enrolment was linked to the Early Childhood Longitudinal Study Birth Cohort (n = 4650). Material hardship was assigned as a composite score of access to food, health care, and housing. Kindergarten teachers rated children's behaviours and activity in the classroom using a five-point Likert scale. Children with summary scores in the bottom decile were classified as displaying ADHD-suggestive behaviours. Logistic regression models were constructed to estimate the association between both BTEX exposure and material hardship on ADHD-suggestive behaviours.

Results: The odds of displaying ADHD-suggestive behaviours were greater in children with combined high-level exposure to BTEX and in those experiencing material hardship (odds ratio 1.54, 95% confidence interval [CI] 1.12, 2.11, and OR 2.12, 95% CI 1.25, 3.59, respectively), adjusting for covariates. These associations were stronger when restricting the study population to urban areas. There was no evidence of interaction between early life BTEX exposure and material hardship, although the effects of BTEX exposure were slightly greater in magnitude among those with higher material hardship scores.

Conclusions: Children exposed to air toxics, material hardship, or both early in life are more likely to display signs of ADHD-suggestive behaviours as assessed by their kindergarten teachers. The associations between exposures to air pollution and to socio-economic hardship were observed in all children but were particularly strong in those living in urban areas.

KEYWORDS
air pollutants, air toxics, child behaviour, socio-economic status, urban environment

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1 | BACKGROUND

Characterised by behaviours including hyperactivity, impulsivity, and inattention, attention-deficit/hyperactivity disorder (ADHD) has a prevalence of 11% in children aged 4-17 years in the United States.[1-3] Typically, diagnosis occurs in children older than 7 years of age due to difficulty ascertaining ADHD-related behaviours in younger children. Identifying behaviours associated with ADHD can provide a path to earlier diagnosis and intervention.[4] Previous research suggests ADHD aetiology and degree of severity involves genetic, environmental, and social factors.[3] Risk factors associated with ADHD are pregnancy and delivery complications, mother's use of tobacco and alcohol, exposure to lead, ambient air pollution, socio-economic stressors, and psychosocial hardship.[2,5-7] These findings have influenced the growing literature involving ADHD and ambient air pollution.[8-10] There is growing interest in understanding how exposure to pollutants may interact with the socio-economic factors that are highly prevalent in disadvantaged populations.[2,11]

Material hardship serves as a more descriptive depiction of low socio-economic status, which has a known effect on child development and well-being.[12] This term integrates measures such as access to food, health care, and housing, providing a more specific assessment of socio-economic status than just low income. Previous research has corroborated that material hardship is associated with cognitive skills and social-emotional competence in children in studies in the United States and UK.[13,14] Thus, material hardship must be taken into consideration in the context of environmental pollution due to the disparities in exposure to air pollution that exist across neighbourhoods.[15,16] The relationship between prenatal air pollution, material hardship, and ADHD has been explored previously in an urban population.[2,9,17] However, there remains a gap in the literature illuminating whether the relationships between ambient air pollutants, material hardship, and neurocognitive outcomes also occur in the broader United States paediatric population. Additionally, it is not clear whether these relationships can be identified earlier in childhood, before ADHD diagnosis.[4]

The objective of this study was to assess the joint relationship between early exposure to common air toxics (benzene, toluene, ethylbenzene, and xylene) and material hardship on teacher-assessed ADHD-suggestive behaviours in a nationally representative sample of children enrolled in kindergarten. We also hypothesised that relationships between air pollutants, material hardship, and ADHD-suggestive behaviours would be stronger in magnitude within the subset of urban children, due to the higher concentrations of pollutants and the context of material hardship in urban communities.

Synopsis

Study question
Are there independent associations between early-life exposure to air pollution, experiencing material hardship, and ADHD-suggestive behaviours in kindergarten among a representative sample of US children?

What's already known
Previous research suggests exposure to air pollution early in childhood may contribute to adverse neurodevelopment in children, including the development of ADHD. Much of this research has studied urban populations.

What this study adds
This study showed that both exposure to air toxics common in ambient air and experiencing material hardship in early life were independently associated with displaying ADHD-suggestive behaviours in the classroom at school entry. The association was found in the general population but was particularly strong in children living in urban areas.

2 | METHODS

2.1 | Cohort selection

The Early Childhood Longitudinal Study Birth Cohort (ECLS-B) is a nationally representative longitudinal study of children born in the United States in 2001 sponsored by The National Center of Education Statistics.[18] Children were followed from birth through kindergarten entry and assessed at 9 months, 2 years, 4 years of age, and entry into kindergarten. At each assessment, children and parent respondents completed survey questionnaires on family demographics, early childcare, preschool, and school environments as they related to development and kindergarten readiness. Teachers were also surveyed at the time of children's kindergarten entry on several academic and behavioural metrics, including signs of ADHD-suggestive behaviours.

For this study, analyses included only children who had parental assessments from enrolment in the ECLS-B through kindergarten, and whose teachers completed the study questionnaires. The analytic cohort was subsequently restricted to include children who had a residential address provided during the baseline visit to link to air pollution exposure and had complete data for all covariates (n = 4650). Figure 1 illustrates the study exclusion criteria and their impact on total sample size. Population totals are reported in this manuscript to the nearest 50 in accordance with restrictions on ECLS-B data presentation.

2.2 | Outcome assessment

Since children in this study population were below the typical age of ADHD diagnosis, teacher-evaluated behaviours were used to identify children displaying ADHD-suggestive behaviours, as opposed to physician diagnosis or parental assessment. The teacher assessment focused on the child's behaviour in the context of the classroom's structured environment. Teachers evaluated six behaviours using a five-point Likert scale, ranging from "Never" to "Very Often," at the kindergarten wave of the ECLS-B. This assessment had teachers rate

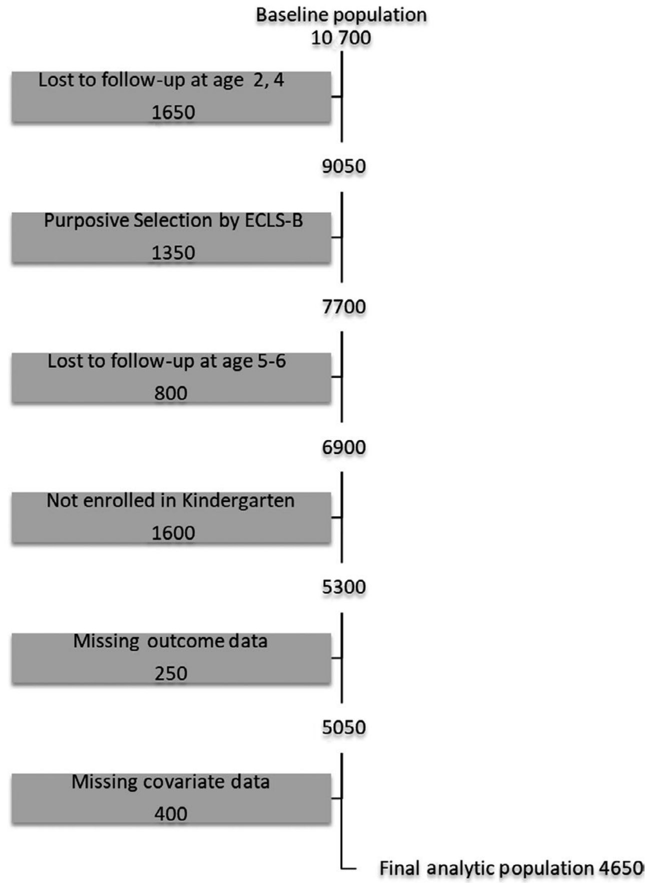

FIGURE 1 Cohort selection for the analytic study population, Early Childhood Longitudinal Study, Birth Cohort 2001

each child's ability to pay attention, conduct work independently, and complete tasks. The assessment also asked teachers to rate behaviours using simple statements, such as “The child is overactive,” “The child is fidgety,” and “The child is impulsive.” These three behavioural items were reverse-coded to ensure consistency in the score, that is, a low score indicates worse behaviours and lower abilities to pay attention and focus. Scores were summed across the six questions. Children within the bottom decile were defined as having ADHD-suggestive behaviours. This approach has been used in previous research within this population.[19] Morgan et al described the disparity in ADHD-suggestive behaviours and diagnosis in this age range within this study population as potentially related to health care utilisation, suggesting that a focus on behaviours would be more sensitive in identifying high-risk children.[19] Similarly, we focused on this subpopulation of children (bottom decile) who had multiple instances of teacher-reported ADHD-suggestive behaviour across domains.

2.3 | Exposure assessment

2.3.1 | Exposure to ambient air toxics

Benzene, toluene, ethylbenzene, and xylene (BTEX) exposures were estimated for each child by linking the ECLS-B with the 2002 National Air Toxics Assessment (NATA) conducted by the Environmental Protection Agency (EPA).[20] NATA combined data from known emission sources with computational models to produce an annual average estimate for each air toxic for every census tract in the United States. We used the 2002 NATA estimates because they are the closest in time to the baseline assessment in the ECLS-B, which occurred when children in the study were 9 months of age. For most children, this baseline visit occurred in 2002.

Consistent with previous studies linking NATA to ECLS-B data,[21] the weighted average pollutant exposures for each ZIP Code were created using the proportion of residential housing within each ZIP Code located within each census tract.[21,22] These data were taken from the United States Housing and Urban Development/United States Postal Service ZIP Crosswalk files. Estimated exposures to each of the BTEX pollutants were assigned using the Zip Code of the children's primary residence at study enrolment (age 9 months).

A measure of combined exposure to BTEX was constructed by assigning those with estimated exposure higher than the median value to each pollutant a value of 1. The sum of these values across the four pollutants was used to create a final composite BTEX score, ranging from 0 to 4. This variable was collapsed into a binary, indicator variable based on having exposure above the median value for all pollutants (ie score of 4). Our goal was not to differentiate the contribution of each of the BTEX components to the outcomes. Rather, we sought to obtain a summary metric that could serve as a marker for distinguishing the children who were highly exposed to BTEX versus children with lower exposures. Given the highly right-skewed distributions of pollutants within the study, we chose to utilise a categorical approach of indexing those who were above the median. This approach makes the exposure measure less susceptible to overly influential outliers occurring when summing the individual estimated concentrations and assessing the total as a continuous, linear term.

2.3.2 | Exposure to material hardship

Material hardship exposure was defined as a composite score measuring food security, insurance coverage, medical care, and housing stability, consistent with previous studies.[2,13] Specifically, material hardship scores were calculated based on parent responses at 9 months of age including (1) receiving food stamps; (2) categorical measure of household food security scale based on standard methods;[23] (3) child insurance coverage; (4) child seen by physician; (5) receiving help with housing; and (6) having moved in the previous 2 years. All measures, except the household food security scale (categorically coded as food secure, food insecure without hunger, and food insecure with hunger), were dichotomized, and negative measures were reverse-coded. The sum of all six measures was used as a final composite material hardship score, ranging from 0 to 7 (a greater score indicative of higher material hardship). The majority of children had low values of material hardship. Children with a score of 3 or greater were treated as exposed to increased material hardship compared with those children with material hardship scores less than 3.

2.4 | Confounders

Covariates to reduce confounding were determined based on known associations with ADHD behaviours, exposure to air pollutants, and material hardship established in the literature. A directed acyclic graph (DAG) describing these associations is presented in Figure S1. The final covariates included in adjusted models were child gender, child race, family socio-economic status (SES), maternal marital status at childbirth, and neighbourhood deprivation index (NDI). Analysis of the DAG did not identify child gender as part of the adjustment set. However, to be consistent with previous research, we included child gender in the final model. For this study, child race was categorised as Black (non-Hispanic), White (non-Hispanic), and Hispanic, with all other reported races, due to low frequencies in the study population, collapsed into an "Other" category.

The SES index created by the ECLS-B study incorporated parental education, occupation, and household income. The NDI, a measure of neighbourhood-level SES disadvantage factors influencing health outcomes, was calculated consistent with previous literature and assigned to each child by linking to the ZIP Code of primary residence at study enrolment.[24] An adapted version of the Home Observation for Measurement of the Environment (HOME) score assessment was included in ECLS-B data collection as a measure of the quality of a child's home learning environment.[25] Subsequent analyses indicated that inclusion of the HOME score did not alter results, and it was not retained in final models. Other research suggests that birth month is highly associated with ADHD symptomology due to age at enrolment in school.[26] To address this, we assessed whether accounting for the birth month in our model would alter our results.

2.5 | Statistical analyses

Logistic regression was utilised to model the association between ADHD-suggestive behaviours and estimated exposure to air pollutants benzene, toluene, ethylbenzene, xylene, and markers of material hardship. The associations are represented by odds ratios (OR) and 95% confidence intervals (CI) as SAS survey procedures do not estimate the relative risk. SAS survey procedures account for complex sampling methods such as weighting, stratification, and clustering in the ECLS-B survey design. Models were constructed separately for each pollutant, for the composite BTEX categorical variable and for the binary material hardship variable. Individual associations, additive associations, and modification between the pollutant and material hardship exposures were assessed with separate models. Analyses were conducted using a single linear term for each pollutant and then as categories to assess linearity. Because relationships between ADHD-suggestive behaviours and individual pollutants (benzene, toluene, ethylbenzene, and xylene) were confirmed as linear, adjusted models were constructed using continuous variables. In order to focus on those with the largest amount of material hardship, only the binary variable for material hardship was assessed in models.

The inclusion of an interaction term between pollutant exposure and material hardship was used to formally assess the presence of effect measure modification (at $\alpha = 0.1$). Analyses were repeated after restricting the population to children who lived in an urban area. The definition of "urban" was derived by the ECLS-B study based on population density, using criteria from the 2000 census.[18] As statistical significance testing of associations was not conducted, we did not implement any methods for multiple comparisons. All analyses were performed in SAS (version 9.3; SAS Institute, Cary, NC).

2.6 | Ethics approval

This study was reviewed and deemed exempt Human Subjects Research by the Institutional Review Board of the Icahn School of Medicine at Mount Sinai.

3 | RESULTS

Socio-economic and exposure characteristics of our study population are presented in Table 1. In the study population of 4650 children, 51.6% were male, 54.3% were white, and 67% had primary caregivers who were married. Only 3.2% of the children experienced 3 or more markers of material hardship and had exposure to high levels of all of the BTEX pollutants.

Unadjusted exposure to all individual pollutants included in BTEX (benzene, toluene, ethylbenzene, and xylene) resulted in increased odds of ADHD-suggestive behaviours (Table 2). Categorical analysis of the pollutants did not display departure from linearity, and so, results are presented only when using a single, linear term. After adjusting for confounding, the magnitude of results for the individual pollutants increased. A similar relationship was seen when examining the combined BTEX variable. The odds of ADHD-suggestive behaviours among children with exposures greater than the median for all BTEX pollutants were 1.32 (1.01, 1.74) times as high as those among children with lower exposure to the combination of pollutants (BTEX). This relationship increased after adjusting for covariates (OR 1.54, 95% CI 1.12, 2.11), including material hardship. Using the binary measure of material hardship, we observed a slight decrease in the odds of ADHD-suggestive behaviours after adjusting for demographics and the combined BTEX variable. However, both high BTEX exposure and material hardship remained independently associated with ADHD-suggestive behaviours in the adjusted models. When including birth month in adjusted models, the estimates were virtually unchanged.

The assessment of effect measure modification between pollutant and material hardship exposures revealed that the interaction term was not statistically significant for the individual pollutant models or the combined BTEX variable (Table 3). Consistent with the formal assessment, the stratum-specific estimates showed only slight differences in the odds of ADHD-suggestive behaviours.

For comparability to a recent New York City cohort study[2] and to examine whether the relationships between BTEX, material

TABLE 1 Sociodemographic characteristics and exposures among the study population of the Early Childhood Longitudinal Study Birth cohort (ECLS-B) 2001 (n = 4650)

Characteristic	% or mean (SD) of study population[a]
Child gender	
Female	51.6
Male	48.4
Child race	
White	54.3
Black	12.8
Hispanic	25.5
Other	7.0
Marital status of primary caregiver	
Married	67.2
Unmarried	32.3
SES Index quintile	
First	18.9
Second	21.0
Third	19.0
Fourth	20.9
Fifth	20.2
Neighbourhood deprivation index	0.50 (1.1)
Benzene	1.3 (0.7) μg/m^3
Toluene	2.8 (2.0) μg/m^3
Ethylbenzene	0.3 (0.3) μg/m^3
Xylene	1.2 (1.2) μg/m^3
BTEX, combined[b]	
Exposure greater than the median for all BTEX pollutants	45.2
Exposure to at least one pollutant is lower than the median level	54.8
Material Hardship, binary[c]	
≥3 hardship markers	7.2
<3 hardship markers	92.8
Combined BTEX and material hardship	
High BTEX exposure with ≥3 hardship markers	3.2
High BTEX exposure with <3 hardship markers	42.0

Abbreviations: BTEX, benzene, toluene, ethylbenzene, and xylenes; SES, socio-economic status.
[a]All results represent weighted values accounting for sampling design of ECLS-B.
[b]BTEX, combined defined as having greater than the median exposure to all four BTEX pollutants (benzene, toluene, ethylbenzene, and xylene).
[c]Exposure to material hardship defined by a score greater than or equal to 3 when summing across parent responses to indicators of material hardship.

hardship, and ADHD-suggestive behaviours were stronger in magnitude in urban areas, the study population was restricted to a smaller subset of children living in urban areas (Table 4). In this subset of urban children, there were increased odds of ADHD-suggestive behaviours for BTEX exposure OR 1.83 95% CI (1.23, 2.73) and for material hardship exposure OR 2.44 95% CI (1.33, 4.49). The assessment of effect measure modification between the pollutant and material hardship exposures in this subset of the study population did not reach statistical significance, but again showed a slight difference in the stratum-specific estimates.

TABLE 2 Individual unadjusted and adjusted[a] odds ratios and 95% confidence intervals for associations between ADHD-suggestive behaviours and benzene, toluene, ethylbenzene, xylene, BTEX, and material hardship, among the subset of Early Childhood Longitudinal Study Birth Cohort 2001 (n = 4650)

	Odds ratio (95% confidence interval)	
Parameter	Unadjusted	Adjusted
Benzene, change in 1 μg/m^3	1.07 (0.89, 1.30)	1.14 (0.92, 1.40)
Toluene, change in 1 μg/m^3	1.01 (0.94, 1.09)	1.03 (0.95, 1.12)
Ethyl benzene, change in 1 μg/m^3	1.17 (0.69, 2.00)	1.36 (0.74, 2.49)
Xylene, change in 1 μg/m^3	1.02 (0.91, 1.14)	1.04 (0.92, 1.19)
BTEX, combined[b]	1.32 (1.01, 1.74)	1.54 (1.12, 2.11)
Binary material hardship[c]	2.47 (1.55, 3.94)	2.12 (1.25, 3.59)

[a]Adjusted for child gender, child race, maternal marital status, socio-economic index, and neighbourhood deprivation index.
[b]BTEX combined, defined as having greater than the median exposure to all four BTEX pollutants (benzene, toluene, ethylbenzene, and xylene) (n = 2000). Reference group consists of individuals who have less than the median exposure for at least one BTEX pollutant. This estimate was obtained from a combined model including binary material hardship.
[c]Exposure to a material hardship defined by a score greater than or equal to 3 when summing across parent responses to indicators of material hardship (n = 300). Reference group consists of individuals who scored less than 3 when summing across indicators of material hardship. This estimate was obtained from a model including BTEX combined.

4 | COMMENT

4.1 | Principal findings

We found that the odds of ADHD-suggestive behaviours were greater in children with combined high-level exposure to BTEX pollutants and in children who experienced multiple markers of material hardship. These associations were more pronounced when restricting the study population to urban areas. This result is congruent with a recent New York City cohort study.[2] In both studies, there was no statistical evidence of interaction between the two variables. Together, our results suggest that both BTEX and material hardship exposure additively contribute to increased odds of ADHD-suggestive behaviours in kindergarten-age children.

TABLE 3 Adjusted[a] odds ratios and 95% confidence intervals for associations between ADHD-suggestive behaviours and benzene, toluene, ethylbenzene, xylene, and combined BTEX, stratified by material hardship among the subset of Early Childhood Longitudinal Study, Birth Cohort 2001 (n = 4650)

	Adjusted odds ratio (95% CI)		
Parameter	Material hardship score ≥3 (n = 300)	Material hardship score <3 (n = 4350)	$P_{interaction}$
Benzene	1.10 (0.62, 1.97)	1.14 (0.93, 1.41)	0.90
Toluene	1.09 (0.86, 1.37)	1.02 (0.94, 1.11)	0.60
Ethyl benzene	2.50 (0.40, 15.8)	1.23 (0.67, 2.24)	0.45
Xylene	1.19 (0.80, 1.76)	1.02 (0.90, 1.17)	0.47
BTEX, combined	1.77 (0.70, 4.47)[b]	1.50 (1.09, 2.07)[c]	0.73

[a]Adjusted models include child gender, child race, maternal marital status, socio-economic status index, neighbourhood deprivation index, and an interaction term between BTEX pollutant and material hardship. Models account for complex sampling design and include sampling weights to represent the population of children born in 2001 in the United States. BTEX combined, defined as having greater than the median exposure to all four BTEX pollutants (benzene, toluene, ethylbenzene, and xylene)

[b]100 individuals meet criterion to be considered "exposed" to BTEX, combined. Reference group consists of individuals who have less than the median exposure for at least one BTEX pollutant.

[c]1900 individuals meet criterion to be considered "exposed" to BTEX, combined. Reference group consists of individuals who have less than the median exposure for at least one BTEX pollutant.

TABLE 4 Adjusted odds ratios and 95% confidence intervals for associations between ADHD-suggestive behaviours, BTEX, and material hardship among the urban subset of Early Childhood Longitudinal Study, Birth Cohort 2001 (n = 3300)[a]

Parameter	Odds Ratio (95% CI)
Model 1[b]	
BTEX combined	1.83 (1.23, 2.73)
Material hardship	2.44 (1.33, 4.49)
Model 2[c]	
BTEX and material hardship score ≥3	2.50 (0.80, 7.83)
BTEX and material hardship score <3	1.76 (1.14, 2.71)
$P_{interaction}$	0.58

[a]Models account for complex sampling design and include sampling weights to represent the population of children born in 2001 in the United States.

[b]Model 1 includes combined BTEX variable, material hardship, and controlled for child gender, child race, maternal marital status, socio-economic status, and neighbourhood deprivation index.

[c]Model 2 includes combined BTEX variable, material hardship, an interaction term between BTEX and material hardship and controlled for child gender, child race, maternal marital status, socio-economic status, and neighbourhood deprivation index.

4.2 | Strengths of the study

Using the ECLS-B cohort, it was possible to examine the association between early-life exposure to air pollutants and later childhood behaviours in a nationally representative sample of US children. This existing study has extensive longitudinal data on residential history, social environments, and childhood behaviours, which facilitated our ability to look at the joint association of BTEX exposure and material hardship in both urban and rural populations. The absolute size of the analytic population was over 4000 children, allowing us to focus in on vulnerable subgroups suffering from considerable amounts of material hardship and exposure to air pollutants, even though their proportion in the population was small. Additionally, the use of a teacher assessment of classroom behaviours avoids the disparities in clinical diagnoses observed in previous research.[19]

4.3 | Limitations of the data

As many air pollutants are highly correlated, it is possible that the associations observed are due to other pollutants that may be correlated with BTEX emissions. Residual confounding could also be due to other spatially varying environmental exposures such as lead. Another limitation may be the potential for selection bias due to the exclusion of children who were not enrolled in kindergarten. Kindergarten is not mandatory across the United States, and it is possible that parents would be reluctant to enrol children who were experiencing behavioural issues. A third limitation is related to the large amount of missing data and loss to follow-up. Multiple imputation of teacher responses would not be appropriate as the missing data mechanism may not be random, even conditioning on other factors. Using a complete case analysis contributed to the resulting small sample size of some groups analysed (ie, BTEX exposure in rural and suburban populations). The lower incidence of material hardship also limited statistical power to detect interactions.

The use of the teacher assessment to identify a subgroup of children with ADHD-suggestive behaviours provided an assessment of the children's behaviours in a structured environment. However, this form of teacher assessment has not been validated as an indicator of eventual ADHD diagnosis, and it is possible that there is misclassification related to classroom behaviours that are not related to ADHD. As a result, we can only discuss these outcomes as suggestive of behaviours that are consistent with ADHD and not a marker of eventual ADHD diagnosis or symptomology. Additionally, the length of time teachers had spent with individual children before completing their behavioural assessment was not a variable collected in the study.

There is also the potential for misclassification of exposure. Our assigned exposure to BTEX pollutants was calculated utilising the NATA conducted in 2002. It is possible that home address of participants may have changed after the initial baseline assessment in 2001/2002. There could also be misclassification of BTEX exposure levels due to differences in exposure sources in rural and urban settings. For example, BTEX exposure may be more likely to occur indoors for children in rural settings and more likely to occur outdoors for those children in urban areas due to differences in exposure source.[27] NATA's exposure estimations focus only on outdoor pollution and thus may be more representative of pollutant concentrations in urban areas. This potential difference between the relative indoor and outdoor levels of pollution may lead to greater misclassification in rural settings.

4.4 | Interpretation

Within our analysis, the odds of ADHD-suggestive behaviours were greater among those with higher exposure to BTEX pollutants, even after adjusting for greater material hardship. These results are consistent with previous studies that observed decrements in measures of neurodevelopment and cognitive function associated with economic hardship and air pollutant exposure in children.[2,21,28] Within this population, primary sources of ambient BTEX exposure are vehicular traffic and stationary sources related to petroleum and industrial activity.[29] Currently, there are no regulatory standards for combined ambient levels of BTEX similar to what the EPA has for the criteria air pollutants. The estimated concentrations applied in this study are below the EPA reference concentration for haematological effects for benzene of 0.03 mg/m^3. There is no reference concentration estimated for developmental effects.[30] Our study adds to the growing literature that suggests that both adverse socio-economic and physical environments, including exposure to air pollutants, collectively affect child cognitive functioning.[31,32]

Although the mechanism remains to be fully understood, there is evidence suggesting air pollution may affect the pathogenesis of ADHD, including potential vulnerabilities at an early age.[33-35] For example, the developing brain from birth to 5 years of age may be most vulnerable to environmental pollutants that can cross the developing blood-brain barrier.[34,36,37] Previous studies have demonstrated the ability of fine particulate matter to cross the blood-brain barrier in rat models.[38] The oxidative stress that occurs in the brain with high exposure to air pollution may ultimately result in ADHD-suggestive behaviours.[34,39,40] These results suggest congruence with the proposed vulnerability in neurological development in children when exposed to air pollutants in early childhood.

4.5 | Conclusions

Exposure to BTEX in ambient air and material hardship early in life were both independently associated with ADHD-suggestive behaviours in children assessed in kindergarten. These results were observed in all children but were stronger in children living in urban areas. This study highlights the need to simultaneously examine both social and environmental contributors to understand the holistic risk of adverse outcomes that tend to cluster within vulnerable communities.

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REFERENCES

1. Visser SN, Danielson ML, Bitsko RH, et al. Trends in the parent-report of health care provider-diagnosed and medicated attention-deficit/hyperactivity disorder: United States, 2003–2011. *J Am Acad Child Adolesc Psychiatry*. 2014;53(1):34-46.e32.
2. Perera FP, Wheelock K, Wang Y, et al. Combined effects of prenatal exposure to polycyclic aromatic hydrocarbons and material hardship on child ADHD behavior problems. *Environ Res*. 2018;160:506-513.
3. Biederman J, Faraone SV. Attention-deficit hyperactivity disorder. *Lancet*. 2005;366(9481):237-248.
4. Feil EG, Small JW, Seeley JR, et al. Early intervention for preschoolers at risk for attention-deficit/hyperactivity disorder: preschool first step to success. *Behav Disord*. 2016;41(2):95-106.
5. Faraone SV, Perlis RH, Doyle AE, et al. Molecular genetics of attention-deficit/hyperactivity disorder. *Biol Psychiatry*. 2005;57(11):1313-1323.
6. Grizenko N, Fortier ME, Zadorozny C, et al. Maternal stress during pregnancy, ADHD symptomatology in children and genotype: gene-environment interaction. *J Can Acad Child Adolesc Psychiatry*. 2012;21(1):9-15.
7. Sagiv SK, Epstein JN, Bellinger DC, Korrick SA. Pre- and postnatal risk factors for ADHD in a nonclinical pediatric population. *J Atten Disord*. 2013;17(1):47-57.
8. Newman NC, Ryan P, Lemasters G, et al. Traffic-related air pollution exposure in the first year of life and behavioral scores at 7 years of age. *Environ Health Perspect*. 2013;121(6):731-736.
9. Aghaei M, Janjani H, Yousefian F, Jamal A, Yunesian M. Association between ambient gaseous and particulate air pollutants and attention deficit hyperactivity disorder (ADHD) in children; a systematic review. *Environ Res*. 2019;173:135-156.
10. Forns J, Sunyer J, Garcia-Esteban R, et al. Air pollution exposure during pregnancy and symptoms of attention deficit and hyperactivity disorder in children in Europe. *Epidemiology (Cambridge, Mass)*. 2018;29(5):618-626.
11. Claudio LC, Landrigan P, Etzel RA. eds. *Impact of poverty, disparity and injustice on children's environmental health*. 2015;528-536.
12. McConnell D, Breitkreuz R, Savage A. From financial hardship to child difficulties: main and moderating effects of perceived social support. *Child Care Health Dev*. 2011;37(5):679-691.

13. Gershoff ET, Aber JL, Raver CC, Lennon MC. Income is not enough: incorporating material hardship into models of income associations with parenting and child development. *Child Dev*. 2007;78(1):70-95.
14. Kiernan KE, Huerta MC. Economic deprivation, maternal depression, parenting and children's cognitive and emotional development in early childhood. *Br J Sociol*. 2008;59(4):783-806.
15. Morello-Frosch R, Shenassa ED. The environmental "riskscape" and social inequality: implications for explaining maternal and child health disparities. *Environ Health Perspect*. 2006;114(8):1150-1153.
16. Perera FP, Rauh V, Whyatt RM, et al. Effect of prenatal exposure to airborne polycyclic aromatic hydrocarbons on neurodevelopment in the first 3 years of life among inner-city children. *Environ Health Perspect*. 2006;114(8):1287-1292.
17. Markevych I, Tesch F, Datzmann T, Romanos M, Schmitt J, Heinrich J. Outdoor air pollution, greenspace, and incidence of ADHD: A semi-individual study. *Sci Total Environ*. 2018;642:1362-1368.
18. Snow K, Derecho A, Wheeless S, et al. *Early Childhood Longitudinal Study, Birth Cohort (ECLS-B), kindergarten 2006 and 2007 data file user's manual (2010-010)*. 2009.
19. Morgan PL, Hillemeier MM, Farkas G, Maczuga S. Racial/ethnic disparities in ADHD diagnosis by kindergarten entry. *J Child Psychol Psychiatry*. 2014;55(8):905-913.
20. EPA. *2002 National-Scale Air Toxics Assessment (NATA)*. https://archive.epa.gov/nata2002/web/html/index.html. Accessed 12/14/2018.
21. Lett LA, Stingone JA, Claudio L. The combined influence of air pollution and home learning environment on early cognitive skills in children. *Int J Environ Res Public Health*. 2017;14(11):1295.
22. Stoner AM, Anderson SE, Buckley TJ. Ambient air toxics and asthma prevalence among a representative sample of US kindergarten-age children. *PLoS ONE*. 2013;8(9):e75176.
23. Bickel G, Nord M, Price C, Hamilton W, Cook J, Service N. *Guide to measuring household food security*. Alexandria, VA: US Department of Agriculture; 2000.
24. Messer LC, Laraia BA, Kaufman JS, et al. The development of a standardized neighborhood deprivation index. *J Urban Health*. 2006;83(6):1041-1062.
25. Elardo R, Bradley RH. The home observation for measurement of the environment (HOME) scale: A review of research. *Dev Rev*. 1981;1(2):113-145.
26. Layton TJ, Barnett ML, Hicks TR, Jena AB. Attention deficit–hyperactivity disorder and month of school enrollment. *N Engl J Med*. 2018;379(22):2122-2130.
27. Mann HS, Crump D, Brown V. Personal exposure to benzene and the influence of attached and integral garages. *J R Soc Promot Health*. 2001;121(1):38-46.
28. Vishnevetsky J, Tang D, Chang HW, et al. Combined effects of prenatal polycyclic aromatic hydrocarbons and material hardship on child IQ. *Neurotoxicol Teratol*. 2015;49:74-80.
29. EPA. *2005 National Emissions Inventory*. 2011; http://www.epa.gov/ttn/chief/net/2005inventory.html#inventorydata. Accessed 4/30/2019.
30. Wilbur S, Wohlers D, Paikoff S, Keith LS, Faroon O. ATSDR evaluation of health effects of benzene and relevance to public health. *Toxicol Ind Health*. 2008;24(5–6):263-398.
31. McEwen BS, Tucker P. Critical biological pathways for chronic psychosocial stress and research opportunities to advance the consideration of stress in chemical risk assessment. *Am J Public Health*. 2011;101(Suppl 1):S131-139.
32. Institute of Medicine. *Genes, behavior, and the social environment: Moving beyond the nature/nurture debate*. Washington, DC: National Academies Press; 2006.
33. Guxens M, Sunyer J. A review of epidemiological studies on neuropsychological effects of air pollution. *Swiss Med Wkly*. 2012;141:w13322.
34. Min JY, Min KB. Exposure to ambient PM10 and NO2 and the incidence of attention-deficit hyperactivity disorder in childhood. *Environ Int*. 2017;99:221-227.
35. Suades-Gonzalez E, Gascon M, Guxens M, Sunyer J. Air pollution and neuropsychological development: a review of the latest evidence. *Endocrinology*. 2015;156(10):3473-3482.
36. Lanphear BP. The impact of toxins on the developing brain. *Annu Rev Public Health*. 2015;36:211-230.
37. Rice D, Barone S Jr. Critical periods of vulnerability for the developing nervous system: evidence from humans and animal models. *Environ Health Perspect*. 2000;108(Suppl 3):511-533.
38. Lockman PR, Koziara JM, Mumper RJ, Allen DD. Nanoparticle surface charges alter blood-brain barrier integrity and permeability. *J Drug Target*. 2004;12(9–10):635-641.
39. Donev R, Thome J. Inflammation: good or bad for ADHD? *Atten Defic Hyperact Disord*. 2010;2(4):257-266.
40. Ng F, Berk M, Dean O, Bush AI. Oxidative stress in psychiatric disorders: evidence base and therapeutic implications. *Int J Neuropsychopharmacol*. 2008;11(6):851-876.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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