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Prenatal exposure to air pollution during the early and middle stages of pregnancy is associated with adverse neurodevelopmental outcomes at ages 1 to 3 years

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Abstract

Background A large body of data shows that fetal brain development is vulnerable to disruption by air pollution experienced by the mother during pregnancy, adversely affecting cognitive and psychomotor capabilities during childhood (De Asis-Cruz et al., Biol Psychiatry 7:480–90, 2022; Morgan ZEM et al., Environ Health 22:11, 2023). This study has sought to identify gestational windows of susceptibility to prenatal exposure to air pollution.

Methods 470 African American and Latina mother/child pairs participated in a prospective cohort study based in the low-income communities of Northern Manhattan and the South Bronx, New York City. Gestational exposure to respirable particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) was assessed through validated models in relation to cognitive and motor development assessed at ages 1, 2, and 3 years using the Bayley-II Scales. Multiple linear regression models and distributed lag models (DLM) were used to identify critical windows of exposure by trimester and week of pregnancy.

Results By linear regression, average exposures to NO_2 during the first and second trimesters and the entire pregnancy were significantly and negatively associated with the mental developmental index (MDI) at age 1. Average exposures to $PM_{2.5}$ during the second trimester and the entire pregnancy were also significantly, inversely associated with age 1 MDI. No significant associations were found between these exposures and MDI at age 2. NO_2 exposure during the first trimester was significantly negatively associated with MDI at age 3. Using DLM, exposures to NO_2 at lags 29–30 weeks (within the first trimester) and $PM_{2.5}$ at lags 17–18 weeks (second trimester) were significantly and inversely associated with MDI at age 1. Significant, inverse associations were found between exposures to NO_2 at lag 29 weeks and $PM_{2.5}$ at lags 27–29 weeks and children's MDI at age 3. No significant associations were found between psychomotor index (PDI) and prenatal exposures to NO_2 or $PM_{2.5}$ at ages 1, 2 or 3.

Conclusions Our finding that prenatal exposure to air pollution in the first and second trimesters was associated with lower scores for cognitive development at ages 1 and 3 is of concern because of the potential consequences

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of these outcomes for long-term functioning. They underscore the need for stronger policies to protect pregnant individuals and offspring, particularly during vulnerable, early life-stage of development.

Keywords Air pollution, Prenatal, Children, Neurodevelopment, Critical windows

Background

The prevalence of neurodevelopmental disorders (NDD), which include learning and intellectual disabilities, has risen in recent decades, reaching 19% among U.S. children aged 3–17 in 2019 and 2020 [1, 2]. While improved awareness, screening, and diagnosis have contributed to this increase, environmental factors have been found to play an important role. These include prenatal exposures to combustion-related air pollutants—fine particulate matter (PM_2), nitrogen dioxide (NO_2), and polycyclic aromatic hydrocarbons (PAH)—that have been linked to adverse effects on early brain development, including poorer cognitive and psychomotor development, IQ reduction, attention problems, attention deficit-hyperactivity disorder (ADHD) behaviors, and structural changes in children's brains [3–6]. In the U.S., there is a pattern of disproportionate exposure to air pollutants in communities of color and low income communities [7].

The focus on the prenatal period of development reflects the large body of data showing that the highly choreographed and complex processes during fetal development are vulnerable to disruption by air pollution, other toxic exposures, and stress experienced by the mother during pregnancy, adversely affecting cognitive and psychomotor capabilities during infancy and childhood [3, 8].

The Distributed Lag Model (DLM) has been used by other investigators to identify critical windows of pre- and post-natal exposure to air pollution during with respect to early child development [8–12]. The studies differ regarding the age at which children were assessed, the methods of assessment; and the sensitive periods identified. Several prior studies of the effects of air pollution have suggested that the mid- to- late gestational periods may be critical windows of exposure [3, 12]. Only one study assessed mental and psychomotor development using the Bayley/ Scales of Infant and Toddler Development [3]. Here, we have used DLM to examine the relationship between prenatal exposure to $PM_{2.5}$ and NO_2 on mental and psychomotor development at ages 1, 2 and 3 assessed using the Bayley Scales of Infant Development – Second Edition (BSID-II) in 470 Latino and African American mother-infant pairs in New York City (NYC). Our goal was to identify vulnerable periods of exposure to inform and support early interventions to reduce exposure to air pollution.

Methods

The cohort

Data are drawn from the Columbia Center for Children's Environmental Health (CCCEH) Mothers and Newborns prospective cohort study, previously described [13, 14]. The participants resided in communities in Northern Manhattan and the South Bronx, which are low-income communities directly served by the Mailman School of Public Health and CCCEH. The Mothers and Newborns cohort includes self-identified African American and Latina women aged 18 – 35 recruited between 1998 and 2006. Women were excluded who initiated prenatal care after the 20th week of pregnancy, had a multiple pregnancy, used tobacco products or illicit drugs, had diabetes or hypertension, were HIV positive, or had not resided in New York City for at least a year. Prenatal visits were conducted in the third trimester of pregnancy (on average at 39.3 weeks of gestation) and children with birth anomalies were not excluded from continuing with the study. Protocols for the cohort were approved by the Columbia University Medical Center Institutional Review Board under protocol number AAAA6110.

Modeling of exposure based on residential address

For each mother/newborn pair, daily exposure to $PM_{2.5}$ and NO_2 at participants' residences during pregnancy was estimated using validated spatio-temporal models described previously [15, 16]. The models incorporated data from the New York City Community Air Survey (NYCCAS), provided by the New York City Department of Health and Mental Hygiene staff, and regulatory data from the Environmental Protection Agency's Air Quality System (AQS) (https://aqsdr1.epa.gov/aqsweb/aqstmp/airdata/download_files.html). The amount/density of candidate spatial predictors were computed, such as traffic and land use-related variables (derived from the New York City Department of City Planning's taxlot database) within 4 different buffer areas around each monitoring site: 100, 300, 500 and 1000 m. Several temporal predictors (temperature, relative humidity, and wind speed) and the mixing depth and air-mass trajectory for each day were included in the models. The level of exposure to each of the two pollutants was estimated for each day of the pregnancy at a spatial resolution of 25×25 m^2. The average values for each week, trimester, and the entire pregnancy were calculated for all mother–child pairs.

Children's neurodevelopmental outcomes

We used the Bayley Scales of Infant Development–Second Edition (BSID-II) to assess cognitive and psychomotor development at 12, 24, and 36 months of age (Bayley 1993). The BSID-II is the most widely used norm-referenced developmental test for young children. The raw score is used to determine the index score for each measure, based off the child's exact age at assessment, generating the mental development index (MDI) and psychomotor development index (PDI) scores. Both the MDI and PDI scores range from 50–150, with lower scores indicating more delays compared to same age peers and higher scores indicate the child is performing above the level of same age peers.

Statistical methods

Data on prenatal exposures

We extracted daily exposure measures of NO_2 and $PM_{2.5}$ during pregnancy for 727 mothers. We then calculated average measures of exposure for the first, second, and third trimesters, and the entire pregnancy, as well as for each week of pregnancy. The first trimester spans gestational week 1 to week 13, the second trimester week 14 to week 26, and the third trimester week 27 to DOB.

Multiple linear regression to test the association between NO_2/$PM_{2.5}$ exposure during different periods of pregnancy and children's neurodevelopmental outcomes

We conducted linear regression models to test for associations between prenatal NO_2/$PM_{2.5}$ exposure in each trimester and neurodevelopmental performance composite scores (MDI/PDI) adjusting for gender, mother's ethnicity, maternal self-report of environmental tobacco smoke (ETS) exposure, maternal education (< high school, ≥ high school), maternal intelligence measured by the Test of Non-verbal Intelligence version 2 (TONI-2), and maternal demoralization. Maternal demoralization is measured using the Psychiatric Epidemiology Research Instrument Demoralization Scale, which contains 27 questions. Each question was rated on a scale from 0 to 4 with higher scores indicating greater psychological distress and participants were queried about symptoms within the previous year. The maternal demoralization score is the average score for the 27 questions. [15]. At age 3, a measure of the quality of the early home caretaking environment (HOME) was available. The Home Observation for Measurement of the Environment (HOME) is an instrument that can be used to measure a child's home environment, including the quality of cognitive stimulation and emotional support provided by the child's family, which contains 8 scales including learning material, language stimulation, physical environment, responsivity, academic stimulation, modeling, variety and acceptance. The home score is the total scores of the 8 scales. [16] We observed that adjusting for this variable changed most of the exposure-outcome associations at age 3 by more than 10% (Supplemental Tables S5-S6). Thus, we included HOME as an additional covariate in analysis of MDI and PDI at age 3.

We examined the effects of exposures to NO_2 and $PM_{2.5}$ during the first, second, and third trimesters, and the entire pregnancy, respectively, on MDI and PDI scores at ages 1, 2, and 3. For MDI or PDI outcomes, we conducted a total of 24 tests (4 pregnancy time periods, 2 exposures, and 3 ages). We calculated false discovery rate (FDR) with the Benjamini-Hochberg (BH) procedure and used 0.05 as the threshold to adjust for multiple comparisons with 24 tests.

Distributed lag models to identify critical windows of exposure to NO_2/$PM_{2.5}$

We conducted DLM to examine the relationship between weekly exposure to NO_2 and $PM_{2.5}$ during pregnancy and MDI and PDI at ages 1, 2, and 3. In DLM, exposure during the week of delivery is termed lag 0; exposure during the week before the delivery is termed lag 1, and so on. Mothers with different gestational durations will have a different number of lags. To be consistent, we considered the first 35 gestational weeks for all mothers. To evaluate the relationships between weekly exposures during pregnancy and neurodevelopmental outcomes using DLM, we adjusted for the same covariates as in the linear regression models. We used a B-spline with 3 degrees of freedom to account for correlations among the 35 gestational weeks and used R package 'DLNM'. For each of the neurodevelopmental outcomes, we conducted 6 tests (2 exposures and 3 ages). Therefore, we used Bonferroni correction to adjust for multiple comparisons and obtained confidence intervals (CIs) on lag coefficients from the DLM models. Specifically, we obtained the coefficient estimates of the lag vectors and their variances and the corresponding CIs with the Bonferroni-adjusted significance level 0.05/6; i.e., 99% CI (1–0.05/6 = 0.9917). If this CI did not include 0, we concluded that there was statistical significance after adjustment for multiple comparisons.

Results

Figure 1 shows the numbers of participants enrolled and those included in the analysis at each age. A total of 520 mother–child pairs had available exposure data and main covariates. The mother–child pairs were further restricted based on availability of MDI and PDI data at ages 1, 2, and 3 years. We compared pairs included in the analyses at each age, with respect to associations between

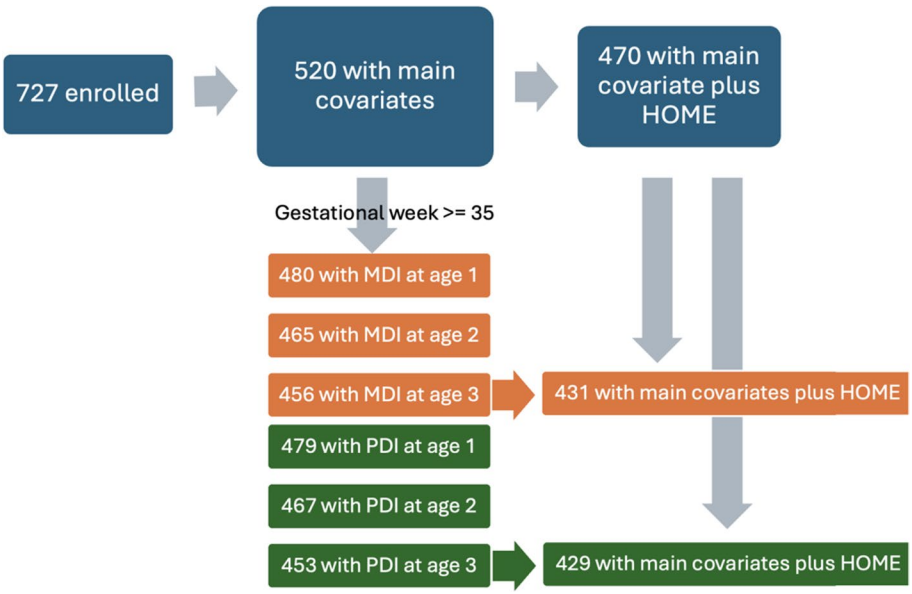

Fig. 1 Sample size flow chart showing the numbers of pregnant people enrolled, and the mother-child pairs not included due to missing exposure data and covariates

MDI and exposures, to those not included because they were missing main covariates. The detailed results are provided in supplementary materials (Supplemental Tables S1-S3). For MDI at age 1, a higher proportion of the excluded group of mothers and children were Latina compared to the included group. For MDI at age 2, there was no significant difference between the included and excluded groups. For MDI at age 3, the excluded group had a higher maternal intelligence score and lower NO_2 and $PM_{2.5}$ exposure levels compared to the included group. Table 1 presents the descriptive statistics of covariate variables and the prenatal exposure level of $PM_{2.5}$ and NO_2.

Association between NO2 and PM2.5 and infant or child neurodevelopmental outcomes by linear regression

Using linear regression models, we found that MDI at age 1 was negatively associated with several measures of prenatal exposure to NO_2 and $PM_{2.5}$ (Table 2). After adjustment for multiple comparisons, average exposure to NO_2 during the first, second trimester and entire pregnancy were significantly and negatively associated with MDI at age 1 (with a BH adjusted p-value < 0.05). Average exposure to $PM_{2.5}$ during the second trimester and the entire pregnancy had significant negative associations with MDI at age 1. No significant associations were found between children's MDI or PDI at age 2 and prenatal exposure to NO_2 or $PM_{2.5}$. In the analysis of children's MDI at age 3, we further adjusted for the quality of the home caretaking environment (HOME) as noted above. Exposure to

Table 1 Descriptive statistics of demographic variables and prenatal exposures to $PM_{2.5}$ and NO_2 for mother–child pairs with all exposures and main covariates ($N = 520$)

Variables	N (%); Mean (SD)
Child sex	
Female	284 (55%)
Male	236 (45%)
Maternal ethnicity	
African American	197 (38%)
Dominican	323 (62%)
ETS (Smoker in the home)	175 (34%)
Maternal education	
High school and higher	310 (60%)
Lower than high school	210 (40%)
Maternal intelligence (TONI)	20.50 (8.72)
Maternal demoralization	1.13 (0.63)
$PM_{2.5}$ at first trimester ($\mu g/m^3$)	17.47 (3.43)
$PM_{2.5}$ at second trimester ($\mu g/m^3$)	16.84 (3.49)
$PM_{2.5}$ at third trimester ($\mu g/m^3$)	16.85 (2.81)
$PM_{2.5}$ over entire pregnancy ($\mu g/m^3$)	17.10 (2.16)
NO_2 at first trimester (*ppb*)	32.13 (6.83)
NO_2 at second trimester (*ppb*)	31.50 (6.21)
NO_2 at third trimester (*ppb*)	31.10 (5.83)
NO_2 over entire pregnancy (*ppb*)	31.58 (5.81)

Table 2 Associations between MDI and prenatal exposures to NO_2/$PM_{2.5}$ by linear regression

Outcome	Exposure	Estimate (95% CI)	Unadjusted P	FDR adj. P
MDI at age 1 (*N* = 482)	NO_2 at first trimester	-0.278 (-0.407, -0.149)	<0.001	0.001
	NO_2 at second trimester	-0.215 (-0.361, -0.069)	0.004	0.024
	NO_2 at third trimester	-0.142 (-0.298, 0.013)	0.072	0.123
	NO_2 at entire pregnancy	-0.258 (-0.413, -0.103)	0.001	0.013
	$PM_{2.5}$ at first trimester	-0.270 (-0.531, -0.009)	0.043	0.123
	$PM_{2.5}$ at second trimester	-0.358 (-0.608, -0.108)	0.005	0.025
	$PM_{2.5}$ at third trimester	-0.134 (-0.452, 0.185)	0.411	0.469
	$PM_{2.5}$ at entire pregnancy	-0.663 (-1.078, -0.248)	0.002	0.014
MDI at age 2 (*N* = 466)	NO_2 at first trimester	-0.103 (-0.266, 0.061)	0.219	0.277
	NO_2 at second trimester	-0.176 (-0.358, 0.007)	0.06	0.123
	NO_2 at third trimester	-0.196 (-0.389, -0.002)	0.047	0.123
	NO_2 at entire pregnancy	-0.182 (-0.376, 0.013)	0.068	0.123
	$PM_{2.5}$ at first trimester	-0.251 (-0.584, 0.082)	0.14	0.209
	$PM_{2.5}$ at second trimester	-0.062 (-0.381, 0.257)	0.704	0.735
	$PM_{2.5}$ at third trimester	0.282 (-0.121, 0.684)	0.17	0.226
	$PM_{2.5}$ at entire pregnancy	-0.075 (-0.606, 0.456)	0.782	0.782
MDI at age 3 additionally adjusting for HOME at age 3 (*N* = 432)	NO_2 at first trimester	-0.189 (-0.339, -0.040)	0.013	0.053
	NO_2 at second trimester	-0.125 (-0.289, 0.040)	0.136	0.209
	NO_2 at third trimester	-0.095 (-0.268, 0.079)	0.284	0.341
	NO_2 at entire pregnancy	-0.168 (-0.343, 0.008)	0.062	0.123
	$PM_{2.5}$ at first trimester	-0.300 (-0.601, 0.001)	0.051	0.123
	$PM_{2.5}$ at second trimester	-0.208 (-0.494, 0.078)	0.153	0.216
	$PM_{2.5}$ at third trimester	0.093 (-0.280, 0.465)	0.626	0.683
	$PM_{2.5}$ at entire pregnancy	-0.444 (-0.923, 0.036)	0.069	0.123

NO_2 during the first trimester remained negatively associated with MDI (BH adjusted p-value = 0.053) (Table 2).

Comparison analysis between the group without HOME at age 3 and the group included in the MDI age 3 analysis suggested that the variable indicating whether the mother completed a high school education was significantly different between the two groups. Therefore, we conducted a sensitivity analysis using inverse probability weighting (IPW) to investigate the influence of excluding the participants without HOME in the MDI age 3 analysis. Specifically, we pooled these two groups (the mother/child pairs without HOME and those with HOME, the latter being included in the MDI age 3 analysis) and calculated the probability of each pair being included in the analysis, using all variables except HOME. We used the inverse of this probability to weight participants to account for the fact that the percentage of participants having completed high school was significantly different between the two groups. We observed that the results from analysis with IPW were very similar to the results without IPW (Supplemental Table S4). Therefore, we concluded that the difference between the two groups did not influence our result.

No significant associations were found between PDI and prenatal exposures of NO_2 and $PM_{2.5}$ after FDR correction (Table 3). We also explored whether there were sex-specific associations. No differences were discovered between males and females.

Distributed lag models to test the effects of weekly exposures of NO2 and PM2.5 during pregnancy

Figures 2 and 3 display the effects of weekly exposures to NO_2 or $PM_{2.5}$ during pregnancy on MDI or PDI at ages 1, 2, and 3, after multiple comparisons adjustment. We observed significant, negative lag effects (with Bonferroni-corrected 99.2% CIs not including 0) of NO_2 and $PM_{2.5}$ on MDI at ages 1 and 3, and a positive lag effect of exposure to $PM_{2.5}$ on PDI at age 3.

Table 4 shows the significant lag effects of NO_2 and $PM_{2.5}$ on MDI and PDI with effect estimates and Bonferroni-adjusted 99.2% CIs. For MDI at age 1, exposure to NO_2 at lags 29–30 had significant, negative effects (Table 4). This was consistent with the results obtained from the regression models where exposure of NO_2 during the first trimester was negatively associated with children's MDI at age 1 (Table 2) because lags 29–30

Table 3 Associations between PDI and prenatal exposures to NO_2/$PM_{2.5}$ by linear regression

Outcome	Exposure	Estimate (95% CI)	Unadjusted P	FDR adj. P
PDI at age 1 (*N* = 481)	NO_2 at first trimester	-0.042 (-0.201, 0.117)	0.602	0.850
	NO_2 at second trimester	-0.036 (-0.214, 0.143)	0.695	0.852
	NO_2 at third trimester	-0.023 (-0.212, 0.166)	0.811	0.885
	NO_2 at entire pregnancy	-0.039 (-0.229, 0.151)	0.687	0.852
	$PM_{2.5}$ at first trimester	-0.099 (-0.417, 0.219)	0.539	0.809
	$PM_{2.5}$ at second trimester	0.204 (-0.102, 0.509)	0.19	0.508
	$PM_{2.5}$ at third trimester	0.024 (-0.365, 0.412)	0.905	0.905
	$PM_{2.5}$ at entire pregnancy	0.096 (-0.412, 0.605)	0.71	0.852
PDI at age 2 (*N* = 469)	NO_2 at first trimester	0.150 (-0.010, 0.310)	0.066	0.508
	NO_2 at second trimester	0.137 (-0.042, 0.316)	0.133	0.508
	NO_2 at third trimester	0.030 (-0.159, 0.220)	0.754	0.862
	NO_2 at entire pregnancy	0.134 (-0.057, 0.324)	0.169	0.508
	$PM_{2.5}$ at first trimester	0.189 (-0.135, 0.513)	0.253	0.600
	$PM_{2.5}$ at second trimester	0.134 (-0.177, 0.445)	0.399	0.722
	$PM_{2.5}$ at third trimester	0.391 (0.001, 0.781)	0.049	0.508
PDI at age 3 additionally adjusting for HOME at age 3 (*N* = 429)	NO_2 at first trimester	0.074 (-0.107, 0.255)	0.421	0.722
	NO_2 at second trimester	0.145 (-0.052, 0.343)	0.149	0.508
	NO_2 at third trimester	0.079 (-0.130, 0.288)	0.456	0.730
	NO_2 at entire pregnancy	0.118 (-0.094, 0.330)	0.275	0.600
	$PM_{2.5}$ at first trimester	0.036 (-0.331, 0.403)	0.848	0.885
	$PM_{2.5}$ at second trimester	0.172 (-0.173, 0.517)	0.328	0.656
	$PM_{2.5}$ at third trimester	0.346 (-0.102, 0.794)	0.129	0.508
	$PM_{2.5}$ at entire pregnancy	0.405 (-0.174, 0.984)	0.17	0.508
	$PM_{2.5}$ at entire pregnancy	0.626 (0.113, 1.139)	0.017	0.405

are within the first trimester of pregnancy. Exposure to $PM_{2.5}$ at lags 17–18 also had significantly negative effects on MDI at age 1 (Table 4) which is consistent with the regression results where the average exposure to $PM_{2.5}$ during the second trimester was negatively associated with MDI at age 1 (Table 2). Exposures of NO_2 at lag 29 and $PM_{2.5}$ at lags 27–29 had significantly negative effects on children's MDI at age 3 (Table 4), which were not revealed in the regression model. With respect to PDI, although exposures of $PM_{2.5}$ during lags 12–13 had significant associations with PDI, the 99.2% CIs almost include 0.

Discussion

In a large sample of mother/child pairs drawn from a prospective cohort of color (African American and Latina) residing in Northern Manhattan and the South Bronx, we have found significant, negative associations between prenatal exposure to two combustion-related pollutants ($PM_{2.5}$ and NO_2) on cognitive (MDI) development at ages 1 and 3 years. Using multiple linear regressions, we found significant, negative associations between MDI at age 1 and average exposure to NO_2 during the first and second trimesters and the entire pregnancy. Average exposure to $PM_{2.5}$ during the second trimester and the entire pregnancy had significant negative effects on MDI at age 1. MDI at age 3 was negatively and significantly associated with exposure to NO_2 during the first trimester. No significant associations with MDI were seen at age 2. No significant associations were found between PDI and exposure to NO_2 or $PM_{2.5}$. The inconsistent results between the outcomes of age 2 and ages 1 or 3 may be due to the decrease we have previously observed in the present cohort in the mean cognitive scores at two years of age [8]. Such a decline on the Bayley-II at two years has been previously reported in low-income families and communities, independent of chemical exposures [1–3], and may contribute to our lack of significant association at 24 months [17–20].

Demonstrating the utility of DLM to identify possible critical windows of exposure on a finer scale, we found significant lag effects of NO_2 and $PM_{2.5}$ on MDI. For MDI at age 1, exposure to NO_2 at lags 29–30 (i.e., weeks within the first trimester) had significant, negative effects, as did $PM_{2.5}$ exposure at lags 17–18 (weeks within the second trimester). With respect to MDI at age 3, exposure to NO_2 at lag 29 and $PM_{2.5}$ at

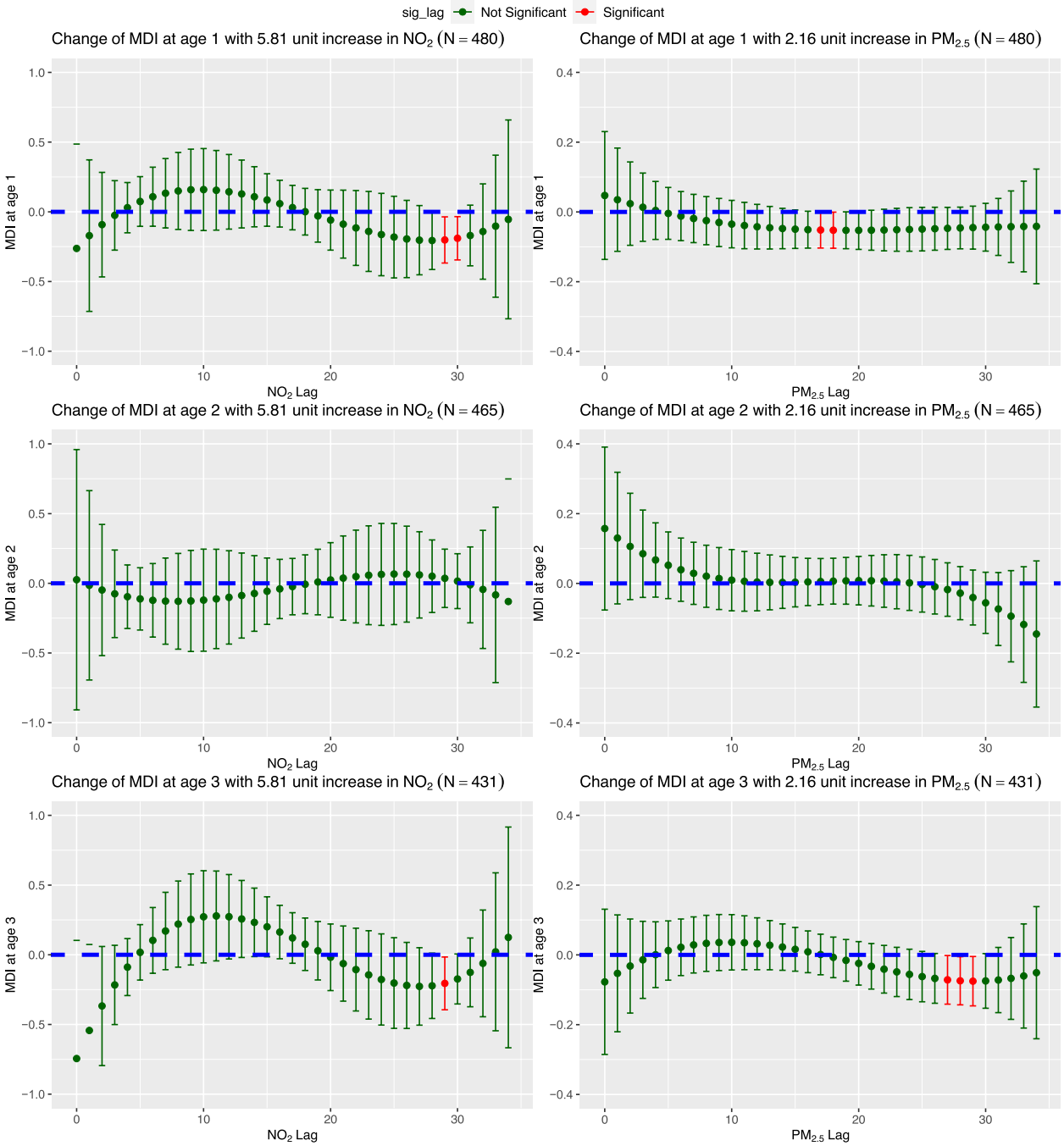

Fig. 2 Lag-specific effects of prenatal exposure to NO_2 (left column) or $PM_{2.5}$ (right column) on children's MDI at ages 1, 2, and 3, for a 1 SD-unit increase in NO_2 or a 1 SD-unit increase in $PM_{2.5}$, where SD is estimated using exposure levels within the entire pregnancy

lags 27–29 (first trimester) had significant, negative effects. Many of these associations agree with what we observed using linear regressions based on trimester of exposure, while several of these associations were not revealed using linear regressions based on trimester of exposure.

The results for PDI were non-significant except for a borderline significant, positive association with exposure to $PM_{2.5}$ during lags 12–13.

Our results in mothers and newborns in NYC contrast with those of a study in 161 Latino mother-infant pairs in Southern California using DLM that pointed to

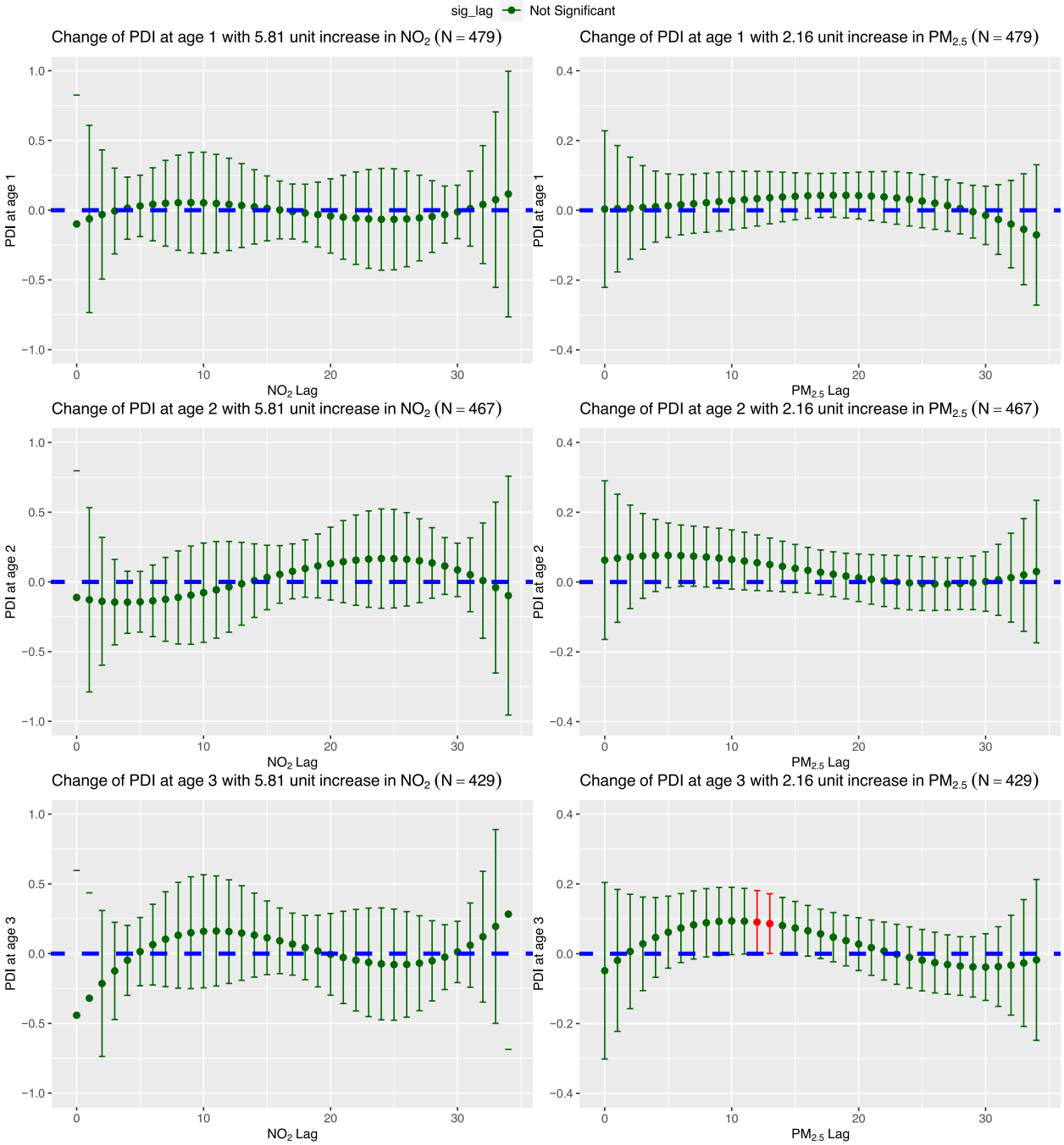

Fig. 3 Lag-specific effects of prenatal exposure to NO_2 (left column) or $PM_{2.5}$ (right column) on PDI at age 1, 2, and 3 for a 1 SD-unit increase in NO_2 or 1 SD-unit increase in $PM_{2.5}$, where SD is estimated using exposure levels within the entire pregnancy

the mid- to-late gestational periods as windows of susceptibility to the effects of $PM_{2.5}$ on cognitive and motor development at age 2. The authors did not assess associations at ages 1 and 3 [3]. The lack of significant findings at age 2 in our study, in contradiction to theirs, may be due to differences in the characteristics of the study populations, exposure levels, and statistical methods, including differing covariates. We also used a more stringent adjustment for multiple comparisons.

Suggested mechanisms for the observed negative effects on neurodevelopment are not fully understood. However, $PM_{2.5}$ and NO_2, two major components of air

Table 4 Significant lag-specific effects of prenatal exposure to NO_2 or $PM_{2.5}$ on children's MDI and PDI, for a 1 SD-unit increase in NO_2 or a 1 SD-unit increase in $PM_{2.5}$, where SD is estimated using exposure levels within the entire pregnancy

Outcome	Exposure	Lag	Estimate (Bonferroni-adjusted CI)
MDI at age 1	5.81-unit increase in NO_2	lag 29	-0.202 (-0.367, -0.036)
		lag 30	-0.190 (-0.345, -0.035)
	2.16-unit increase in $PM_{2.5}$	lag 17	-0.052 (-0.104, -0.000)
		lag 18	-0.052 (-0.104, -0.001)
MDI at age 3	5.81-unit increase in NO_2	lag 29	-0.205 (-0.395, -0.016)
	2.16-unit increase in $PM_{2.5}$	lag 27	-0.071 (-0.141, -0.002)
		lag 28	-0.074 (-0.143, -0.005)
		lag 29	-0.075 (-0.146, -0.004)
PDI at age 3	2.16-unit increase in $PM_{2.5}$	lag 12	0.091 (0.000, 0.181)
		lag 13	0.086 (0.001, 0.172)

pollution, have been found to contribute to elevated oxidative stress, leading to inflammatory responses, DNA damage, and disruption of cellular signaling pathways [14]. A more complete mechanistic discussion is beyond the scope of the work, but others have considered the impact on different brain-based developmental processes on gestation [8].

Limitations of the present study include the fact that our cohort includes only African American and Latina women of lower income, so our results may not be generalizable to populations of other ethnicities and socioeconomic status. Further, we considered only $PM_{2.5}$ and NO_2 and were not able to assess the associations with other air pollutants. We also did not have data on postnatal exposure to these pollutants and were not able to assess their possible impact on cognitive and motor development.

Advantages of the study include our well- characterized multiethnic cohort drawn from communities of color and low income who are most at risk from air pollution, a larger sample size than previous studies, and the ability to assess effects by week of exposure as well as by trimester and entire pregnancy.

Conclusion

Our findings using linear regression and DLM suggest that the first and second trimesters, and certain weeks therein, may be vulnerable windows of exposure to air pollution, resulting in lower scores for cognitive development at ages 1 and 3. This is of concern because of the potential consequences for long-term functioning. These findings add to a large body of evidence on the vulnerability of the fetal developmental period to air pollution and underscore the need for stronger policies to protect this vulnerable life stage.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12940-024-01132-9.

Supplementary Material 1.

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Authors' contributions

FP, KR and JH wrote the main textand contributed to the database, YM and SW conducted statistical analyses and prepared figures and tables, ZR conducted expposure modeling, VH, VR, AM contributed to the database. All authors reviewed the manuscript.

Data availability

Data available upon request.

Declarations

Competing interests

The authors declare no competing interests.

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