PARTICULATE MATTER, MICRONUTRIENT SUPPLEMENT, AND EARLY CHILDHOOD DEVELOPMENT

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ABSTRACT

Despite increasing evidence on the importance of in-utero air pollution exposure on later-life economic outcomes, little is known about the mechanisms underlying such effects. This paper examines the impacts of fetal exposure to air pollution in critical prenatal windows on child development using a panel administrative data on over 1,800 children and their mothers from Southern Shaanxi Province, China from the year 2013-2015, combined with a flexible fixed effects regression strategy. Then, I assess how micronutrients might moderate such impacts induced by prenatal exposure to $PM_{2.5}$. I find that fetal air pollution exposure in the second trimester of pregnancy significantly reduces children's later performance on the Bayley Mental Development Index and Bayley Psychomotor Development Index. Further, the micronutrient treatment moderates roughly one-third the damages induced by exposure to $PM_{2.5}$.

Keywords: Air pollution, nutrition supplements, early childhood development, micronutrient

BIOGRAPHICAL SKETCH

Xuqian Ma is a MS student at Cornell University Dyson School of Applied Economics and Management, with a concentration in international and development economics. Her research interests lie in early childhood nutrition, maternal and child health, and gender. Prior to Cornell, she received a B.S. in economics from the University of Minnesota Twin Cities. She worked as a research assistant at Stanford Rural Education Program (REAP), China Philanthropy Research Institute, and Peking University China Center of Agricultural Policy (CCAP). She is going to pursue a PhD in Health Policy at the University of California Berkeley starting from this fall.

This document is dedicated to all Cornell graduate students.

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CHAPTER 1

INTRODUCTION

Globally, 630 million children under 5 years old and 1.8 billion children under 15 years old are exposed to ambient fine particulate matter ($PM_{2.5}$) levels beyond WHO air quality standards (WHO, 2018). Pregnant women who are exposed to air pollution are more likely to give birth to babies that are premature or low birth weight (WHO, 2018). Air pollution also has an adverse impact on neurodevelopment, resulting in worse cognitive test outcomes and a detrimental impact on mental and motor development (WHO, 2018).

In the past few years, researchers have increasingly recognized the long-term impacts of fetal exposure on children, benefiting from access to newly large-scale administrative data sources to track children over time (Almond et al., 2018). Sanders (2012), for example, investigates the influence of prenatal total suspended air particulates exposure on educational outcomes. Isen et al. (2017) also examined how the Clean Air Act of 1970 impacted the employment and incomes of individuals who were influenced by air pollution in their early years of life. However, it remains poorly understood how fetal exposure to air pollution in some critical pregnancy trimesters or prenatal windows impacts child development in later life. In addition, to my best knowledge, it is still unknown how micronutrients might moderate such impacts on child development induced by prenatal exposure to $PM_{2.5}$.

To look closer into these issues, I first assess the in utero trimester effect of fetal $PM_{2.5}$ exposure from 2011-2013 on mental and motor development in early childhood during 2013-2015 in a sample of 1802 children from southern Shaanxi Province, China. My richest model specification estimates the effect of $PM_{2.5}$ exposure in each trimester of pregnancy on children's Bayley Scale Index of Development with county fixed effects and survey wave fixed effects, controlling for the child's gender and months of age, whether the child was breastfed only, caregiver's level of education, whether mother was at home taking care of the child, household income, and air temperature. My estimation allows me to control for potential time-variant confounders and time-invariant omitted variables. Then, I evaluate the moderation effect of a randomized micronutrient supplement intervention based on the previous estimation.

The rest of the paper proceeds as follows. Section 2 touches on the biological mechanism behind the link between $PM_{2.5}$ exposure in certain prenatal windows and later neurodevelopment, and exsiting evidence on micronutrients' protective effects against damage induced by $PM_{2.5}$. Section 3 describes the sources and features of the datasets in my study. Section 4 illustrates the empirical methodology applied in my study. Section 5 presents the main findings of my study. Section 6 presents the conclusions of the paper.

CHAPTER 2

BACKGROUND

2.1 $PM_{2.5}$ exposure in critical prenatal periods and later neurodevelopment

An increasing amount of evidence demonstrates that prenatal exposure to pollution has deleterious consequences for future neurodevelopment. PM exposure is associated with a higher risk of neurodegeneration and neurodevelopmental problems (Morris et al., 2021). Gestational PM exposure (exacerbated by mitochondrial impairment in the metabolically active neonatal brain) has a negative influence on neurodevelopment and may make the brain more susceptible to cognitive impairment later in life (Morris et al., 2021). $PM_{2.5}$ exposure during pregnancy has been shown to change brain morphology by increasing oxidative stress and inflammation in the central nervous system (Bansal et al., 2021; Calderón-Garcidueas et al., 2008a,b; Calderón-Garcidueas et al., 2011; Cowell et al., 2019). Direct placental translocation of ultrafine particles, placental and systemic maternal oxidative stress and inflammation evoked by both fine and ultrafine PM, epigenetic alterations, and potential endocrine effects that influence long-term health are some of the biological mechanisms at work (Johnson et al., 2021).

However, our understanding about the timing of vulnerable prenatal periods for brain development remains insufficient. Health science research suggests that cerebral cortex cellularity increases most rapidly between gestational weeks 15 and 20, while fetal defenses against $PM_{2.5}$ neurotoxicity (such as the blood-brain barrier and hepatic detoxification) develop heterogeneously across trimesters (Ackerman, 1992; Bansal et al., 2021; Giancotti et al., 2019; Goasdoué et al. 2017).

Fetal brain development is shown to be linked with prenatal $PM_{2.5}$ exposure in some critical trimesters or prenatal windows in pregnancy. In a longitudinal birth cohort research in Mexico City, Bansal et al. (2021) examined the effects of daily prenatal $PM_{2.5}$ exposure on 320 children. Higher prenatal $PM_{2.5}$ exposure was associated with poorer vigilance and inhibitory control results in children aged 9–10 years (Bansal et al., 2021). The development of vigilance and inhibitory control in preadolescent children are shaped in large part by their exposure to $PM_{2.5}$ in the second and third trimesters of pregnancy (Bansal et al., 2021). Another study evaluated the effect of daily prenatal $PM_{2.5}$ exposure on 267 full-term urban children whose mothers were primarily minorities with less than 12 years of education (Chiu et al., 2016). Increased $PM_{2.5}$ exposure in specific prenatal windows, from weeks 12 to 40, may be associated with lower memory and attention functions, with varying results depending on the child's sex (Chiu et al., 2016).

Bharadwaj et al. (2017) assessed the effect of trimester CO exposure in Santiago, Chile, between 1992 and 2001 on middle school test scores later in 2002-2010. The richest model specification estimates the effect of trimester CO pollution exposure on middle school test scores with year and month fixed effects and sibling fixed effects, controlling for ozone pollution levels, year and month dummies interacted with three monitor dummies, gender dummy, a host of weather controls, mother's characteristics, and the number of alert days during the pregnancy for each trimester. It concludes that third-trimester CO exposure is associated with a 0.036 standard deviation decline in 4th-grade math test scores and a 0.042 standard deviation fall in 4th-grade language test scores.

As a robustness check, they used PM_{10} as their primary pollutant and found qualitatively identical findings, despite the inaccurate claim that PM does not penetrate the placental barrier and only harms fetuses via respiratory and cardiovascular effects on the mother. This is an indirect estimate for the trimester effect of prenatal PM_{10} exposure, but the comparable estimation for $PM_{2.5}$ exposure might be considerably different since finer particulate matters like $PM_{2.5}$ cross the placenta. In addition, aside from the fact that test scores may have predictive values for children's IQ, they are not a direct indicator for their cognitive ability or neurodevelopmental function.

Based on these results, I will look for evidence on how fetal exposure to $PM_{2.5}$ impacts later neurodevelopment in early childhood using environmental data and administrative data.

2.2 Moderation effect of micronutrient supplements

Micronutrients, such as B vitamins, vitamin C, vitamin E, and vitamin D, have protective effects against damage induced by PM on human health (Péter et al., 2015).

The B vitamins, which include vitamin B2, vitamin B6, vitamin B12, and folate, are critical cofactors and substrates in one-carbon metabolism, since they are involved in the folate and methionine cycles (Péter et al., 2015). Numerous methylation processes, as well as the production of lipids, nucleotides, and proteins, are all part of one carbon metabolism (Péter et al., 2015). Many illnesses, such as cardiovascular disease, neurological disease, and cancer, are associated with a perturbation in one carbon metabolism (Péter et al., 2015; Fiorito et al., 2014; Abbenhardt et al., 2014). The effects of air pollution, gene polymorphisms in one carbon metabolism, and dietary intake of methyl nutrients (folate, vitamin B6, vitamin B12, and methionine from food sources) on HRV were studied in older persons from the Boston region (Péter et al., 2015; Baccarelli et al., 2008). It was found that genetic variations and dietary micronutrient intake can modulate the health effects of $PM_{2.5}$ (Péter et al., 2015; Baccarelli et al., 2008).

In humans, vitamin E and vitamin C are the most fundamental lipid-soluble and water-soluble antioxidants (Péter et al., 2015). Individuals exposed to coal-burning pollutants from an electric-power station were tested for the effects of PM-induced oxidative stress (Péter et al., 2015; Possamai et al., 2010). In the presence of PM exposure, antioxidant consumption was enhanced, and the oxidative stress defense system was activated (Péter et al., 2015; Possamai et al., 2010). Vitamin E and C supplementation reduced lipid and protein damage indicators and improved enzymatic and non-enzymatic antioxidant defenses (Péter et al., 2015; Possamai et al., 2010). The capacity of dietary antioxidants to boost the activity of antioxidant enzymes is critical, as these endogenous enzymes are vital for neutralizing the damaging effects of free radicals like hydrogen peroxide and superoxide. As a result, antioxidant supplementation may be beneficial in lowering oxidative stress caused by air pollution in the body (Péter et al., 2015).

In another study, individual plasma antioxidant concentrations (uric acid and vitamins C, A, and E) and 10 antioxidant genes were investigated in a London-based bidirectional case crossover research to see if they may affect the response to PM in terms of hospital admissions for COPD or asthma (Whyand et al., 2018; Canova et al., 2012). PM_{10}'s impact on asthma/COPD exacerbations was altered by serum vitamin C. Low levels of uric acid and vitamin E also had a comparable (albeit smaller) effect (Whyand et al., 2018; Canova et al., 2012).

In the long run, PM may also have a deleterious influence on vitamin D levels in human bodies (Péter et al., 2015). Vitamin D can be synthesized in the skin through the action of sunshine, which is the most important source of the vitamin, accounting for roughly 80% to 90% of human needs (Péter et al., 2015). The quantity of UVB radiation from the sun that reaches the earth's surface is mostly determined by air pollution (Péter et al., 2015). Vitamin D levels were assessed in children in a Delhi study who lived either in a location with high levels of air pollution or in a less polluted region of the city (Péter et al., 2015; Agarwal et al., 2002). The mean serum 25(OH)D levels of children living in Delhi's severely polluted neighborhood were 54 percent lower than those of children living in a less polluted area (Péter et al., 2015; Agarwal et al., 2002). In another study, the vitamin D level of healthy women in Tehran was found considerably lower than that of women in Ghazvinian, a less polluted city in Iran (Péter et al., 2015; Hosseinpanah et al., 2010). Thus, supplementary dietary intake of vitamin D is essential for people living in regions with high levels of air pollution (Péter et al., 2015).

However, to my best knowledge, it remains unknown if micronutrients could moderate the adverse neurodevelopment effect induced by $PM_{2.5}$. In this study, I will use a randomized micronutrient supplement trial to look for evidence on how micronutrients supplement might moderate such effect on child development induced by prenatal exposure to $PM_{2.5}$.

CHAPTER 3

DATA

I combine different sources of data to study the effect of $PM_{2.5}$ exposure in different trimesters of pregnancy on child development in Southern Shaanxi Province, China. The household surveys from a randomized micronutrient powder intervention generate a wide array of information on the socioeconomic and health indicators of children and their caregivers or mothers. I merge $PM_{2.5}$ data derived by a machine learning approach and weather data from monitors with the household survey data. My main specifications are at the child level.

3.1 The micronutrient powder intervention and the early childhood development data

The early childhood development data come from a micronutrient powder home fortification program in Southern Shaanxi Province, China (Luo et al., 2017). The sample was selected in 174 townships from 11 nationally designated poverty-stricken counties[1] in southern Shaanxi Province based on two exclusion criteria to ensure a large enough rural sample of children aged 6–11 months old: (1) to exclude the county seat township in each county and (2) to exclude the townships which had no village with a population greater than 800. Two villages were randomly selected from each township and an additional village was selected in randomly chosen townships to meet power requirements, which generates a final sample of 351 villages. A list of all

[1] China set poverty alleviation as a priority for development since the 18th CPC National Congress in 2012 and one in every three counties was labeled "poverty-stricken" in 2013 (CGTN, 2020).

registered births over the past 12 months was obtained from the local family planning official in each village. Two cohorts of children aged 6-11 months old were enrolled in the program in April 2013 and October 2013, respectively. Children with severe disease were not included in the sample selection, which might raise selection bias concern in this study if air pollution is a potential cause of severe disease. In this sense, I might underestimate the impact of $PM_{2.5}$ exposure on child development. Overall, the baseline sample included 1802 children.

234 villages (1192 children) were allocated to the MNP (micronutrient powder) treatment group, and 117 villages (610 children) were allocated to the control group. The program lasted for 18 months for both cohorts (from April 2013 to October 2014 for cohort 1 and from October 2013 to April 2015 for cohort 2). Child, caregiver or mother, and household characteristics are well-balanced in the treatment group and the control group (see table 2 in appendices). Three follow-up surveys were conducted every 6 months. 975 children in the MNP group and 515 children in the control group showed up in all 3 follow-up surveys. Thus, it constructs an unbalanced panel data set in nature with a relatively high attrition rate. 18.20% of children in the treatment group and 15.57% of children in the control group did not show up in all 3 waves of the follow-up surveys, respectively. If attrition is correlated with the level of prenatal $PM_{2.5}$ exposure, for example, if remote households had higher attrition rate and were exposed to lower level of $PM_{2.5}$, the relying estimation strategy in this study would be biased. Table 5 shows that although the correlation between attrition (a dummy variable with 1 as lost and 0 as show up) and $PM_{2.5}$ exposure in the first and

third trimester of pregnancy are weakly significant, the size of the coefficients is too small to cause any problem in my estimation strategy in this study.

In the MNP group, caregivers were given a 6-month supply of MNP sachets every 6 months. Each daily-dose sachet contains 6 mg of iron as well as zinc, vitamins A, C, D, B_1, B_2, B_6, B_{12}, and folic acid (see Table 1) and is recommended for children aged 6–36 months (Luo et al., 2017). The full ingredients were based on China's general standard for supplementary food supplements and were authorized for use in the national program to distribute MNPs through local clinics in poverty-stricken counties (piloting for the national program began after this study outside the study regions) (Luo et al., 2017; Ministry of Health and Standardization Administration of the People's Republic of China, 2008). At the first distribution, caregivers were also informed of the causes and consequences of anemia and were given oral and written instructions on how to mix one sachet of MNP per day with the child's food. They were also given a plastic storage envelope to store the empty packets. In the follow-up surveys, the enumerators tallied unused and empty packets to assess compliance. The mean number of sachets consumed declined from 16 sachets per month in the first follow-up survey to 13 sachets in the third follow-up survey when the expected consumption of sachets is 1 per day and 30 per month.

The primary caregiver was identified as the individual at the household most responsible for childcare (typically the child's mother or grandmother). In the baseline and follow-up surveys, the primary caregivers were surveyed on prenatal care and nutrition during pregnancy, the child's health status at birth, the child's diet and nutrition, the child’s health conditions after birth, caregiver’s level of education, employment status and salary, and other household socioeconomic characteristics. In the baseline and the follow-up surveys, all children were administered the Bayley Scales of Infant Development (BSID) Version I which consists of two subindices: Mental Developmental Index (MDI), which assessed cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language; and Psychomotor Developmental Index (PDI), which assessed gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger) (Lowe et al., 2012). In 1992, BSID was formally adapted to the Chinese language and setting and was scaled based on an urban Chinese sample (Luo et al., 2017; Huang et al., 1993; Li et al., 2009). This study employed an officially modified version of the test following earlier published research in China that utilized the BSID to measure infant development (Luo et al., 2017; Rubio-Codina et al., 2016; Chang et al., 2013; Wu et al., 2011). All BSID enumerators attended a week-long training on how to administer the BSID. The test was administered at households using a standardized set of toys and a detailed scoring sheet.

The BSID took into consideration child age in days, and whether the child was premature at birth. Raw scores of the two subindices were normalized to a score for age-standardized score based on a reference group of healthy children in China supplied by the testing company. These normalized scores had an expected mean of 100 and a standard deviation of 16, with a score below 80 for each subindex defined as impairment. However, BSID are moderately predictive of developmental delay in very preterm children (Luttikhuizen dos Santos et al, 2013). In very preterm children, MDI and PDI scores explain less than half of the variance in later cognitive and motor functioning (Luttikhuizen dos Santos et al). If BSID underestimates the development potential of the preterm children in my sample, I might overestimate the impact of $PM_{2.5}$ exposure on child development.

3.2 Birth data

The child's birthday was obtained from the child's birth certificate. Gestational age was also obtained from the child's birth certificate. Children in this study were born in the year 2012 or 2013. On average, their gestational age at birth was 39 weeks. Their conception period spans from year 2011 to 2013. I assign weeks 1-13 to first trimester, weeks 14-26 to second trimester, and weeks 27-birth to third trimester. There are in total of 70 children in the baseline whose caregivers failed to report their gestational age due to unknown reasons. Thus, I cannot assign trimesters to these 70 children.

3.3 $PM_{2.5}$ data

The air pollution data come from a near real-time air pollutant concentration database called TAP (Tracking Air Pollution in China). The TAP database is derived by machine learning approaches that combine information from multiple data sources, including ground measurements, satellite retrievals, emission inventories, chemical transport model simulations, meteorological fields, and land use data (Geng et al., 2021). The machine learning process might produce classical measurement errors in the $PM_{2.5}$ data, which will cause attenuation bias in my main coefficients of interests.

The original $PM_{2.5}$ data have a geographic resolution of 10 km × 10 km and are averaged to a daily mean by the publishers, which I average to the county × day level from 2011-2015. The final data consist of daily mean $PM_{2.5}$ level in 11 counties in Southern Shaanxi Province, China. Since the exact birth date and gestational age can be obtained from the data, I can compute trimesters and trace back the history of gestational exposure to $PM_{2.5}$ (similar to Bharadwaj et al. 2014). However, I do not have information on where the mother lived during pregnancy. I assume that the county in which the child was administered the BSID is the county in which the mother resided during pregnancy (similar to Sanders, 2012). This might introduce a potential source of measurement error in assignment, which I will discuss further in section 4.4. Thus, the $PM_{2.5}$ exposures are computed for each child independently and are based on daily measurements throughout each trimester of pregnancy in the county where the child was administered the BSID. In this way, $PM_{2.5}$ exposures determined for all children born on the same day who were administered the BSID in the same county are the same.

There are in total of 70 children in the baseline whose caregivers failed to report their gestational age due to unknown reasons. If the socioeconomic characteristics of the 70 children are different from those of other children whose gestational ages were reported, the estimation of the impact of $PM_{2.5}$ exposure on child development might be inaccurate due to selection bias.

The average $PM_{2.5}$ concentrations over 2011 - 2013 are about 42 ug/m^3. Figure 1 indicates significant seasonal variation in the $PM_{2.5}$ average distribution. In winter, the level of $PM_{2.5}$ concentrations is much higher in all counties.

The TAP estimates are favored over monitor data for the following reasons. First, TAP integrates the strengths of various data sources to provide atmospheric composition concentration estimations with complete coverage on a daily scale (Geng et al., 2021). Second, it can capture smaller geospatial variation of $PM_{2.5}$ level at county level when monitor data are not available in the rural area.

3.4 Weather data

Weather data come from National Centers for Environmental Information. Global Surface Summary of the Day is derived from The Integrated Surface Hourly (ISH) dataset (NCEI, 2021). The final data consist of daily average air temperature in 3 cities in Southern Shaanxi Province, China. Again, like in section 3.3, I do not have information on where the mother lived during pregnancy. I assume that the city in which the child was administered the BSID is the city in which the mother resided during pregnancy. I generate the air temperature control variable by computing the number of days exceeding 25 °C in the city where the child was administered the BSID in his/her mother’s gestational period because temperature sensitivity is evident in multiple periods of early development, ranging from the first trimester of gestation to age 6–12 month. An extra day with mean temperatures above 32 °C in utero and in the first year after birth is associated with a 0.1% reduction in adult annual earnings at age 30 (Isen et al., 2017). In addition, the pollution measurements are derived from machine learning method and are based on daily average air temperature, which might cause collinearity between the pollution measurements and the air temperature measurements. Using the number of days with extreme hot temperature could fix the potential collinearity in the estimation model.

CHAPTER 4

EMPIRICAL FRAMEWORK

4.1 The human capital production function

I model child development, BSID at the time of survey ($BSID_t$), as a human capital production function, which is a function of $PM_{2.5}$ exposure in each trimester of pregnancy (PM_t), child characteristics (X), caregiver characteristics (M), household characteristics (H), and environmental factors (E):

$$BSID_t = f(PM_t, X, M, H, E)$$

The estimation uses BSID as the dependent variables and $PM_{2.5}$ exposure in each trimester as the independent variables of interest. All children were administered four rounds of BSID assessment. I treat each round of measurement of each child as one observation in the sample. For every observation, the time-invariant independent variables are repeated, and the time-variant independent variables are updated (similar to Currie and Neidell, 2005). Thus, I do not control for child fixed effects since my observations are at the child level and including child fixed effects would absorb all the variation in the estimation.

4.2 Econometric model

In order to estimate the latent effect of in-utero $PM_{2.5}$ exposure on child development later in life, I estimate the following model:

$$BSID_{ijct} = \alpha + w_t + c_c + \beta_1 PM_{ijct}^{1st} + \beta_2 PM_{ijct}^{2nd} + \beta_3 PM_{ijct}^{3rd} + \beta_4 PM_{ijct}^{post} + \delta X_{ijct} + \omega M_{ijct} + \varphi H_{ijct} + \gamma E_{ct} + \epsilon_{ijvt} \quad (1)$$

In equation (1), the dependent variable $BSID_{icjt}$ is Bayley MDI or PDI of child i, born to mother j, in county c, at time t. Only one child in each household was selected into the sample. The Bayley scores reflect the assessment on the day the child was administered, which is a long-term consequence shaped by genetics, health condition, and home environment from conception to the day of evaluation. The first three terms on the right-hand side of the equation are $PM_{2.5}$ exposures in three trimesters of pregnancy. The coefficients of interest are the βs, the parameters indicating the effect of $PM_{2.5}$ exposure in different trimesters on child development. After the child was born, both $PM_{2.5}$ exposure during pregnancy and cumulative $PM_{2.5}$ exposure after the child was born can affect the child development. Thus, I also add $PM_{2.5}$ exposure (PM^{post}) after the child was born to the model, mean $PM_{2.5}$ exposure from when the child was born to when the survey was conducted, as a control variable.

X_{ics} is a vector of child covariates, including the child's months of age, gender, and whether he/she was exclusively breastfed at the time the survey was conducted. M_{jcs} is a vector of caregiver covariate, including caregiver's level of education, whether the mother was at home taking care of the child at the time the survey was conducted. H_{ijc} is a vector of household covariates, including household income. E_{cs} is a vector of weather control, including number of days exceeding 25 °C. To capture the unexplained time-invariant spatial effect on child development and $PM_{2.5}$ concentrations, I control for county fixed effects, c_c. I additionally control for wave fixed effects, w_t, to capture any residual variation in this dimension of the model. To account for how unobserved determinants of BSID are likely correlated across children within a county and wave, I cluster the standard errors (ϵ_{ics}) at county by wave level.

4.3 Moderation effect of micronutrient powder intervention

In order to assess the moderation effect of the micronutrient treatment on child development damage triggered by $PM_{2.5}$ exposure, I estimate the following model:

$$BSID_{ijct} = \alpha + w_t + c_c + \beta_0 MNP_{ijct} + \beta_1 PM_{ct}^{1st} + \beta_2 PM_{ct}^{1st} * MNP_{ijct} +$$
$$\beta_3 PM_{ct}^{2nd} + \beta_4 PM_{ct}^{2nd} * MNP_{ijct} + \beta_5 PM_{ct}^{3rd} + \beta_6 PM_{ct}^{3rd} * MNP_{ijct} +$$
$$\beta_7 PM_{ct}^{post} + \beta_8 PM_{ct}^{post} * MNP_{ijct} + \delta X_{ict} + \varphi H_{ijc} + \gamma E_{ct} + \epsilon_{ijvt} \quad (2)$$

where the outcome variable Bayley MDI or PDI (*BSID*), independent variables of interest (*PM*), and other control variables (*X*, *H*, *E*) are the same as in equation (1), except for here I add in interaction terms of $PM_{2.5}$ exposure in each trimester (*PM*) and the micronutrients powder treatment (*MNP*). The coefficients of interest are the βs. They indicate the moderation effect from the micronutrient treatment to offset the impaired development potential happened in conception. In equation (2), I also control for wave and county fixed effects to account for the randomization procedure and cluster the standard errors at county by wave level. My identification strategy here relies on the random assignment of the micronutrient treatment. It estimates the intent-to-treat effect of the micronutrient powder intervention, recognizing heterogeneous and imperfect caregiver compliance with the MNP supplements.

4.4 Potential threats to causality and identification strategy

Similar to Roth (2020) and Lavey et al. (2014), there are three main econometric challenges in identifying the causal impact of $PM_{2.5}$ exposure on child development. First, in this study, pollution is not randomly assigned and the level of $PM_{2.5}$ exposure in each trimester of pregnancy might also be correlated with other socioeconomic, cultural, or environmental factors that codetermines child development. For example, infants born in high-pollution regions are more likely to be born to younger, less educated, unmarried mothers who are less likely to obtain prenatal care during the first trimester (Currie and Neidell, 2005). In this study, I assume when mothers possess higher level of education but live in relatively less industrial regions during the time of pregnancy, they are more likely to migrate to nearby town to seek better employment opportunities, leading to higher prenatal $PM_{2.5}$ exposure at the same time. Thus, mother's level of education might be correlated with both prenatal $PM_{2.5}$ exposure and her child's later development. There might also be other unobservable covariates that affect mother's migration decision. In this case, confounding becomes a major concern in the estimation due to omitted variable bias. In order to identify the causal effect of prenatal $PM_{2.5}$ exposure on child development, I adopt the fixed effects model illustrated in section 4.2 which allows me to control for many time-invariant covariates.

The second challenge is heterogeneity in avoidance behavior. For example, families with higher socioeconomic status usually have higher demand for air pollution information and defensive technologies such as masks and air purifiers (Greenstone et al., 2021). In China, the air quality monitoring and disclosure program launched during 2013-2014 expanded public access to pollution information and increased households' awareness on air pollution, which leads to consumption pattern change to avoid pollution exposure and higher willingness to pay for housing in less polluted areas (Barwick et al., 2019). However, in Southern Shaanxi of year 2011-2013, it is less likely that rural villagers had any sort of knowledge on air pollution or showed any incentive to practice avoidance behavior. Households in my sample also share similar socioeconomic and cultural background. Thus, heterogeneity in avoidance behavior among villagers in my sample is less likely to happen.

Another potential threat to the causality identified in this study is measurement error matching pollution data to individual exposure level. Due to the large geographical variance in pollution, even within precisely defined areas, measurement error in pollution exposure is likely to exist (Moretti and Neidell, 2011). In this study, $PM_{2.5}$ exposure is assigned at the county level, which erases the potential spatial variation of $PM_{2.5}$ level in each geographical unit.

To test these potential threats to causality in my estimation equation, I conduct a set of robustness tests (1) using a subsample of mom who took care of her child at home at the time the survey was conducted; (2) using AQI index measures (number of days exceeding $PM_{2.5}$ level of 35 or 75); (3) using a dummy for impairment (scores below 80); (4) adding mean exposure one year before 3-month preconception as placebo; (5) adding season of birth as additional control variable. I find that the results are robust to these specifications. I will discuss the results further in detail in section 5.2.

CHAPTER 5

ESTIMATION RESULTS

In this section, I present the results estimating the impact of prenatal $PM_{2.5}$ exposure on later child development, as well as the moderation effect of micronutrients supplement on the impact of prenatal $PM_{2.5}$ exposure. Besides the $PM_{2.5}$ concentration variables, all regression control for child months of age, child gender, if child was breastfed only at the time the survey was conducted, caregiver's level of education, whether mother was at home taking care of the child at the time the survey was conducted, household income, and number of days exceeding 25 °C. Wave and county fixed effects are controlled for in all estimations. All standard errors are clustered at county by wave level, the level of sample selection, to allow for county- and wave-specific correlated errors over time.

5.1 Prenatal $PM_{2.5}$ exposure and later child development

Table 6 presents the association between Bayley scores and prenatal $PM_{2.5}$ exposure. Column 1 shows that $PM_{2.5}$ exposure in the second trimesters of pregnancy has a negative significant effect on Bayley MDI. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.1436 unit decrease in Bayley MDI. $PM_{2.5}$ exposure in the first trimester of pregnancy also shows a slightly negative significant effect on Bayley MDI. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.0919 unit decrease in Bayley MDI.

Column 2 shows that $PM_{2.5}$ exposure in the second trimester of pregnancy has a negative significant effect on Bayley PDI. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.1966 unit decrease in Bayley PDI. $PM_{2.5}$ exposure in the third trimester of pregnancy also shows a weakly negative significant effect on Bayley PDI. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.0871 unit decrease in Bayley PDI.

To summarize the findings in Table 6, fetal exposure to $PM_{2.5}$ is detrimental to both mental and psychomotor development of babies aged 6-30 months old. Specifically, $PM_{2.5}$ exposure in the second trimester of pregnancy is more critical predictor of the potential loss of mental development potential and psychomotor skill accumulation. The results in Table 6 indicate a strong negative effect of prenatal $PM_{2.5}$ exposure on early childhood development. Consider that the mean $PM_{2.5}$ exposure in the second trimester of pregnancy in my sample is 43.29 ug/m^3 (see table 4), the mean outcome in this study causes a 0.39 standard deviation loss in Bayley MDI and a 0.53 standard deviation loss in Bayley PDI.

My results in Table 6 show similar patterns as in Bansal et al. (2021) and Chiu et al. (2016). that the second trimester of pregnancy is a vital period for fetal brain development. Increased fetal $PM_{2.5}$ exposure in this window is associated with decreased neurodevelopmental capacity in later childhood. The biological mechanism behind it may be that gestational weeks 15-20 is a key period for both cerebral cortex cellularity and fetal defenses against $PM_{2.5}$ neurotoxicity (Ackerman, 1992; Bansal et al., 2021; Goasdoué et al. 2017; Giancotti et al., 2019).

5.2 Moderation effect of micronutrient supplements

Next, I assess how micronutrient supplements moderate the adverse effects from exposure to $PM_{2.5}$ on child development. Table 7 shows that the micronutrient powder treatment is associated with a moderation of roughly one-third of the damages induced by exposure to $PM_{2.5}$. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.1878 unit decrease in Bayley MDI. However, 0.0688 unit of the damage is offset after $PM_{2.5}$ interacts with the micronutrient intervention. The situation for Bayley PDI is similar despite the size and significance of the coefficients are larger. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.2503 unit decrease in Bayley PDI while 0.0863 unit of damage is ameliorated by the interaction with the micronutrient intervention. These results indicate that micronutrients might play a protective role on child development when fetal exposure to $PM_{2.5}$ is hard to avoid.

5.3 Robustness checks

I test the robustness of my main results in section 5.1 and 5.2 using multiple alternations to my main specifications in section 4.2 and 4.3.

Subsample of mom who took care of her child at home

To ease the concern about elective migration mentioned in section 4.4, I restrict my estimation to the subsample of mom who took care of her child at home at the time the survey was conducted. I assume mothers who lived close to her child after the child was born were less likely to migrate during pregnancy. The coefficients in Table 8 and 9 are consistent with my main results in section 5.1 and 5.2 that $PM_{2.5}$ exposure in the second trimester of pregnancy has a negative significant effect on Bayley MDI and Bayley PDI and the micronutrient powder treatment is associated with a moderation of roughly one-third of these damages.

The air quality index (AQI)

My main estimation equations assess the impact of level concentrations of $PM_{2.5}$ exposure on child development. However, the impact of $PM_{2.5}$ exposure might not be linear and higher concentrations of $PM_{2.5}$ exposure might trigger worse child development outcomes. Hence, I convert mean $PM_{2.5}$ exposures into number of days with AQI 50 and AQI 100 in which AQI 50 corresponds to daily mean $PM_{2.5}$ concentration exceeding 35 $\mu g/m^3$ and AQI 100 corresponds to daily mean $PM_{2.5}$ concentration exceeding 75 $\mu g/m^3$. The coefficients in Table 10 are consistent with my main results in section 5.1. In the AQI 50 setting, only the number of days in the second trimester shows a negative significant effect on Bayley MDI and Bayley PDI. In the AQI 100 setting, the number of days in both first and second trimesters shows a negative significant effect on Bayley MDI and Bayley PDI; the number of days in the third trimester shows a negative significant effect on Bayley PDI as well. In addition, the size of the coefficients becomes larger as I restrict the AQI from 50 to 100. The coefficients in Table 11 are also consistent with my results in section 5.2. The micronutrient powder treatment is associated with a moderation of roughly one-third of these damages induced by exposure to $PM_{2.5}$ in both the AQI 50 setting and the AQI 100 setting.

Using a dummy for impairment (BSID below 80)

My estimations so far have all focused on the impact of $PM_{2.5}$ exposure on child development in general. However, it is unclear how prenatal exposure to $PM_{2.5}$ might cause the extreme case of impairment in development potential, which indicates a Bayley score of below 80. Table 12 shows that being exposed to $PM_{2.5}$ in the second trimester of pregnancy has a positive significant effect on the incidence of impairment. In my sample where the mean exposure to $PM_{2.5}$ in the second trimester of pregnancy is 43.29 ug/m^3, the mean outcomes correspond to a 13% and 10% increase in the probability of impairment in Bayley MDI and Bayley PDI, respectively. But as indicated by table 13, the micronutrient powder treatment is associated with a moderation of roughly one-third of the incidence of Bayley MDI impairment induced by exposure to $PM_{2.5}$ and roughly half of that for Bayley PDI.

Placebo test

Similar to Roth (2020) and Lavey et al. (2014), I conduct a placebo test to test the possibility that my estimates may capture unobserved time-varying factors that are correlated with both $PM_{2.5}$ exposure and child development. I use the level of air pollution in the year before the 3-month preconception as the explanatory variable of interest since $PM_{2.5}$ exposure during preconception (the 3 months ahead of conception) was negatively associated with offspring mental and psychomotor development (Li et al., 2021). Tables 14 and 15 show that these coefficient estimates are not significant, which supports the causal interpretation of my main results in section 5.1 and 5.2.

Season of birth

Season of birth might be associated with later child development outcomes. Buckles and Hungerman (2013) found that among women who try to conceive, winter births are disproportionally realized by teenagers and the unmarried and family background controls explain nearly half of season-of-birth's relation to adult outcomes. Hence, I add season of birth as an additional control variable to indirectly control for unobserved time-unvarying maternal characteristics that are both correlated with pollution and child development. The coefficients in Tables 16 and 17 are consistent with my main results in section 5.1 and 5.2 that $PM_{2.5}$ exposure in the second trimester of pregnancy is more critical predictor of the potential harm to Bayley MDI and Bayley PDI and the micronutrient powder treatment is associated with a moderation of roughly one-third of these damages.

CHAPTER 6

CONCLUSION

In this study, I combine the environmental pollution dataset with a panel early childhood development administrative dataset from a randomized micronutrient supplements intervention to examine the trimester effect of fetal $PM_{2.5}$ exposure on early childhood neurodevelopment, as well as whether micronutrient supplements might moderate such effect, in a sample of 1802 Chinese children from southern Shaanxi Province. My richest model specification estimates the effect of $PM_{2.5}$ exposure in each trimester of pregnancy on Bayley Scale Index of Development with county fixed effects and wave fixed effects, controlling for the child's gender and months of age, whether the child was breastfed only, caregiver's level of education, whether mother was at home taking care of the child, household income, and air temperature.

I find that fetal exposure to $PM_{2.5}$ in the second trimester shows a negative significant effect on Bayley Mental Development Index (MDI) and Bayley Psychomotor Development Index (PDI). A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.0919 and 0.0871 unit decrease in Bayley MDI and Bayley PDI, respectively. Consider that the mean $PM_{2.5}$ exposure in the second trimester of pregnancy in my sample is 43.29 ug/m^3, the mean outcome in this study causes a 0.39 standard deviation loss in Bayley MDI and a 0.53 standard deviation loss in Bayley PDI.

The micronutrient powder treatment is associated with a moderation of roughly one-third of the damages induced by $PM_{2.5}$. A 1 ug/m^3 increase in $PM_{2.5}$ exposure is associated with a 0.1878 and 0.2503 unit decrease in Bayley MDI and Bayley PDI, respectively. However, 0.0688 and 0.0863 unit of the damage on Bayley MDI and PDI is offset respectively after interacting with the micronutrient intervention.

The results are robust to multiple alternations including when (1) using a subsample of mom who took care her child at home at the time the survey was conducted; (2) using AQI index measures (number of days exceeding $PM_{2.5}$ level of 35 or 75); (3) using a dummy for impairment (scores below 80); (4) adding mean exposure one year before 3-month preconception as additional control variable; (5) adding season of birth as additional control variable.

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APPENDICES

Figure 1: $PM_{2.5}$ exposure (ug/m^3) in year 2011-2013 by county and season

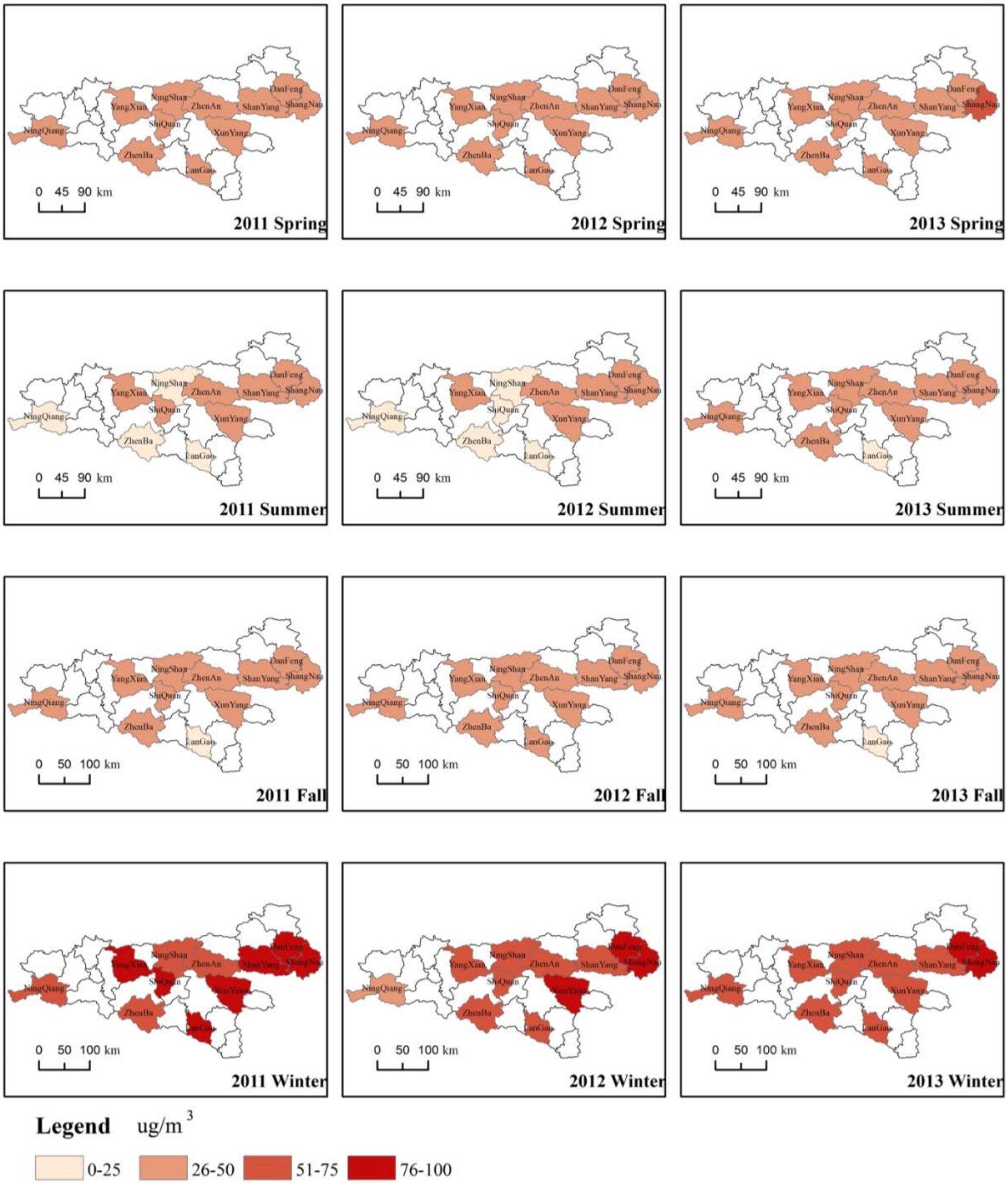
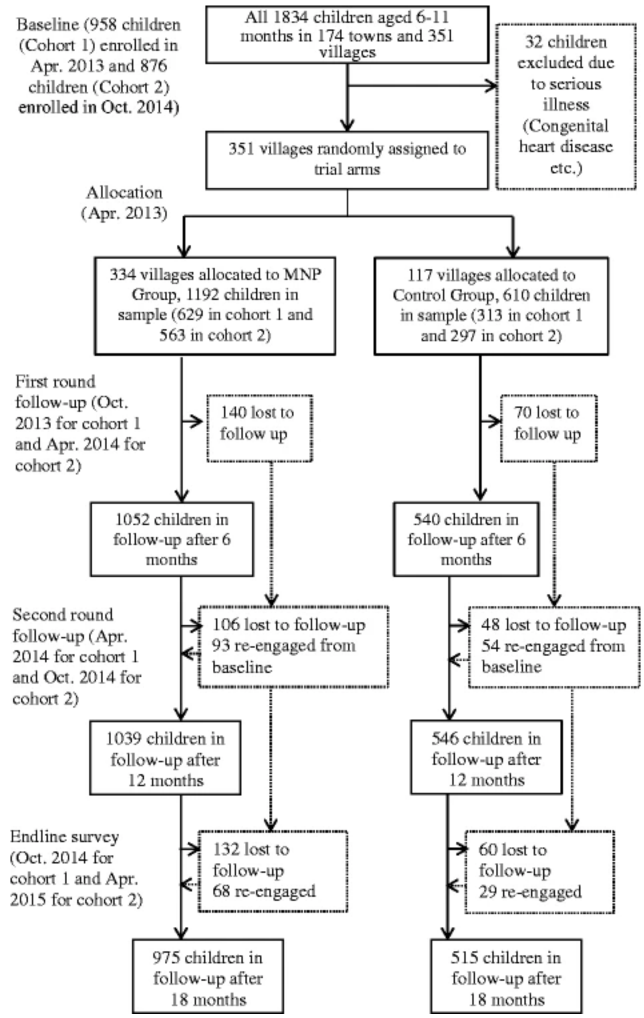


Figure 2: Trial profile. MNP = Micronutrient Powder



Note. From “The effect of a micronutrient powder home fortification program on anemia and cognitive outcomes among young children in rural China: A cluster randomized trial,” by Luo R, Yue A, Zhou H, Shi Y, Zhang L, Martorell R, Medina A, Rozelle S and Sylvia S, 2017, *BMC Public Health*, 17(1), p. 5. Copyright 2017 by BMC Public Health.

Table 1: Composition of NurtureMate home fortification powders

Nutrients	Unit	Average content per packet (1 g)	RNI or AI in China (6–11 months) per day[b]	RNI or AI in China (12–36 months) per day
Iron (ferrous lactate)	mg	6.0	10	12
Zinc (zinc sulfate)	mg	4.80	8	9
Vitamin A	μgRE	200	400	500
Vitamin C	mg	50.0	50	60
Vitamin D	μg	5.0	10	10
Vitamin E	mg	1.55	3	4
Vitamin B1	mg	0.30	0.3	0.6
Vitamin B2	mg	0.50	0.5	0.6
Vitamin B6	mg	0.30	0.3	0.5
Vitamin B12	μg	0.5	0.5	0.9
Folic acid	μg	66	80	150
Niacin	mg	3.0	3	6
Energy	kJ	15		
Protein	g	0		
Fat	g	0		
Carbohydrate	G	0.9		

Note. From “The effect of a micronutrient powder home fortification program on anemia and cognitive outcomes among young children in rural China: A cluster randomized trial,” by Luo R, Yue A, Zhou H, Shi Y, Zhang L, Martorell R, Medina A, Rozelle S and Sylvia S, 2017, *BMC Public Health*, 17(1), p. 3. Copyright 2017 by BMC Public Health.

Table 2: Baseline characteristics by experimental arm (N = 1802)

Characteristics	**Control Group (*n* = 610)**	**Free MNP Group (*n* = 1192)**	***P*** [2]
Social economic status			
Age in months[3]	9.46 ± 1.90	9.50 ± 1.83	0.75
Girls (%)	49.0 (299)	46.5 (544)	0.26
Low birth weight (%)	4.4 (27)	4.7 (56)	0.80
First birth (%)	62.3 (380)	62.7 (747)	0.88
Families received social security support (%)	24.4 (149)	23.2 (276)	0.45
Caregiver and mother characteristics			
Mother is primary caregiver (%)	79.2 (483)	81.8 (975)	0.31
Maternal education ≥9 years (%)	78.4 (478)	82.3 (981)	0.07
Maternal age (year)	26.2 ± 4.3	26.5 ± 4.7	0.25
Child feeding practices			
Ever breastfed (%)	87.7 (535)	89.3 (1064)	0.36
Exclusive or predominant breastfeeding <6 Months (%)	37.7 (230)	37.8 (451)	0.97
Still breastfed ≥12 Months (%)	39.2 (239)	37.3 (444)	0.14
Ever formula-fed (%)	63.4 (387)	66.4 (792)	0.07
Supplementary feeding after six months (%)	65.9 (402)	65.3 (778)	0.87
Parenting practices			
Played with baby yesterday with toys (%)	49.8 (304)	46.7 (557)	0.12
Sang song to baby yesterday (%)	29.0 (177)	28.7 (342)	0.78
Child nutrition status			
Hemoglobin concentration (g/L) [4]	109.3 ± 13.0	109.1 ± 12.5	0.71
Anemia prevalence (%)[4]	49.3 (297)	48.5 (573)	0.88
Child development status			
MDI test score[5]	97.2 ± 17.0	96.6 ± 16.9	0.87
PDI test score[6]	90.1 ± 18.0	90.1 ± 16.7	0.85

Note. From “The effect of a micronutrient powder home fortification program on anemia and cognitive outcomes among young children in rural China: A cluster randomized trial,” by Luo R, Yue A, Zhou H, Shi Y, Zhang L, Martorell R, Medina A, Rozelle S and Sylvia S, 2017, *BMC Public Health*, 17(1), p. 6.

Table 3: Descriptive statistics.

Variable	Wave 0	Wave 1	Wave 2	Wave 3
If the child is male (1/0)	0.53 (0.50)	0.53 (0.50)	0.53 (0.50)	0.53 (0.50)
Firstborn (1/0)	0.62 (0.49)	0.62 (0.49)	0.62 (0.49)	0.62 (0.49)
Premature (1/0)	0.11 (0.31)	0.11 (0.31)	0.11 (0.31)	0.11 (0.31)
Low birth weight (1/0)	0.07 (0.25)	0.07 (0.25)	0.07 (0.25)	0.07 (0.25)
Months of age	8.98 (1.86)	15.10 (1.84)	21.01 (1.87)	26.98 (1.83)
Household income (1000 RMB)	30152.34 (27212.23)	30021.50 (27538.60)	29848.73 (26612.28)	29430.75 (26839.97)
Relationship of caregiver with child				
Mother	48.72%	49.37%	47.79%	48.49%
Father	43.21%	42.45%	44.25%	43.51%
Parental grandmother	6.46%	6.48%	6.32%	6.19%
Parental grandfather of maternal grandmother	1.61%	1.70%	1.65%	1.81%
Caregiver's level of education				
No schooling	4.34%	4.53%	4.36%	4.37%
Primary school	22.76%	22.83%	23.26%	23.54%
Junior middle school	54.47%	54.09%	54.49%	54.61%
Senior middle school	15.41%	15.22%	14.79%	14.66%
Vocational school	2.50%	2.70%	2.53%	2.22%
University and above	0.61%	0.63%	0.57%	0.61%
Mother was at home taking care of the child at the time the survey was conducted (1/0)	0.85 (0.36)	0.72 (0.45)	0.67 (0.47)	0.66 (0.48)
Observations	1802	1592	1585	1490

Notes: Data comes from a micronutrient powder home fortification program carried out by Peking University China Center of Agricultural Policy. The program followed up 1802 children and their caregivers/mothers from the year 2013-2015 four times including the baseline survey. Most mothers did not migrate and were at home taking care of their children. Mothers were less likely to migrate when their children were young and need intensive care from mothers.

Table 4: Summary statistics of $PM_{2.5}$ exposure (ug/m^3).

Variable	Mean	Std. Dev.	Min	Max
$PM_{2.5}$ in first trimester	43.93	17.35	20.29	84.39
$PM_{2.5}$ in second trimester	43.29	17.04	20.29	84.62
$PM_{2.5}$ in third trimester	41.57	15.97	20.29	80.59
$PM_{2.5}$ from born to survey	42.67	6.32	23.81	70.72
Observations	6020			

Notes: $PM_{2.5}$ exposures are computed for each child independently and are based on daily measurements throughout each trimester of pregnancy in the county where the child was administered the BSID. In this way, $PM_{2.5}$ exposures determined for all children born on the same day who were administered the BSID in the same county are the same.

Table 5: Attrition (1=lost, 0=show up).

	Attrition	Attrition	Attrition	Attrition
$PM_{2.5}$ in first trimester	-0.0001 (0.0002)			0.0009* (0.0005)
$PM_{2.5}$ in second trimester		-0.0003 (0.0003)		-0.0001 (0.0003)
$PM_{2.5}$ in third trimester			-0.0004 (0.0003)	0.0012** (0.0006)
Wave fixed effects	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
Observations	6928	6928	6928	6928

Notes: All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 6: Basic Regression Results.

	MDI	PDI
$PM_{2.5}$ in first trimester	-0.0919*	-0.0236
	(0.0411)	(0.0417)
$PM_{2.5}$ in second trimester	-0.1436***	-0.1966***
	(0.0420)	(0.0333)
$PM_{2.5}$ in third trimester	-0.0426	-0.0871
	(0.0432)	(0.0516)
$PM_{2.5}$ from born to survey	-0.3721***	-0.9501***
	(0.1090)	(0.1109)
Child months of age	-0.4891***	-0.1846
	(0.1735)	(0.3301)
Child is male	-2.3755***	-0.8154
	(0.5225)	(0.4905)
Breastfed only	-0.5746	1.4989
	(1.9026)	(1.6320)
Caregiver level of education	2.3615*	-1.1837
Primary school	(1.2476)	(1.3593)
Junior middle school	5.4641***	1.4494
	(1.2211)	(1.4978)
Senior middle school	7.6151***	2.0601
	(1.5147)	(1.7991)
Vocational school	14.5328***	2.0179
	(1.8551)	(2.0465)
University and above	5.9863*	-1.8586
	(3.2974)	(3.7709)
Mom was at home taking care of the child	1.1633	-0.8716
	(0.7103)	(0.7847)
Household income (in 1000 yuan)	0.0355***	0.0455***
	(0.0122)	(0.0126)
Number of days air temperature ≥ 25℃	-0.0259	0.0062
	(0.0349)	(0.0356)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 6.1: Bayley MDI regression results with decomposition of R^2.

Regressor	Coef.	R^2 decomposition (%) Owen	Group
Number of days in first trimester	0.0900** (0.0409)	1.8275	7.2208
Number of days in second trimester	0.1426*** (0.0422)	4.0645	
Number of days in third trimester	-0.0398 (0.0432)	1.3287	
Number of days from born to survey	-0.3683*** (0.1095)		2.0916
Child months of age	-0.4763*** (0.1757)		30.6039
Child is male	-2.3878*** (0.5188)		2.1342
Breastfed only	-0.5740 (1.9007)		0.2971
Caregiver level of education			10.4412
Primary school	2.3336* (1.2483)		
Junior middle school	5.4434*** (1.2214)		
Senior middle school	7.6381*** (1.5196)		
Vocational school	14.7874*** (1.8880)		
University and above	6.0189* (3.3806)		
Mom was at home taking care of the child	1.1944 (0.7112)		1.2452
Household income (in 1000 yuan)	0.0356*** (0.0122)		1.8067
Number of days air temperature ≥ 25℃	-0.0248 (0.0351)		9.1134
Wave dummies			35.0460
County dummies			9.1134
Overall R^2	0.1604		
Observations	5737		

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 6.2: Bayley PDI regression results with decomposition of R^2.

Regressor	Coef.	R^2 decomposition (%) Owen	Group
Number of days in first trimester	-0.0262 (0.0422)	1.0145	11.9843
Number of days in second trimester	-0.1991*** (0.0334)	9.4454	
Number of days in third trimester	-0.0902* (0.0521)	1.5244	
Number of days from born to survey	-0.9647*** (0.1119)		15.7836
Child months of age	-0.1724 (0.3301)		21.3379
Child is male	-0.8850* (0.4884)		0.3324
Breastfed only	1.5302 (1.6300)		0.8118
Caregiver level of education Primary school	-1.1442 (1.3552)		3.2583
Junior middle school	1.4748 (1.4950)		
Senior middle school	2.0240 (1.7970)		
Vocational school	2.0286 (2.0644)		
University and above	-2.5925 (3.7146)		
Mom was at home taking care of the child	-0.9086 (0.7921)		1.1901
Household income (in 1000 yuan)	0.0460*** (0.0126)		2.8560
Number of days air temperature ≥ 25℃	0.0049 (0.0355)		10.0242
Wave dummies			32.4213
County dummies			10.0243
Overall R^2	0.1238		
Observations	5737		

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 7: Moderation effects.

	MDI	PDI
MNP	2.0165	2.0115
	(3.2660)	(4.1529)
$PM_{2.5}$ in first trimester	-0.0743	-0.0145
	(0.0445)	(0.0598)
MNP* $PM_{2.5}$ in first trimester	-0.0263	-0.0188
	(0.0430)	(0.0618)
$PM_{2.5}$ in second trimester	-0.1878***	-0.2503***
	(0.0442)	(0.0368)
MNP* $PM_{2.5}$ in second trimester	0.0688**	0.0863***
	(0.0312)	(0.0317)
$PM_{2.5}$ in third trimester	-0.0191	-0.1194*
	(0.0502)	(0.0650)
MNP* $PM_{2.5}$ in third trimester	-0.0327	0.0473
	(0.0442)	(0.0475)
$PM_{2.5}$ from born to survey	-0.3345***	-0.8557
	(0.1159)	(0.1262)
MNP* $PM_{2.5}$ from born to survey	-0.0548	-0.1589
	(0.0899)	(0.1344)
Child months of age	-0.4825	-0.1860
	(0.1761)	(0.3319)
Child is male	-2.3608	-0.8392
	(0.5237)	(0.4858)
Breastfed only	-0.6389	1.4085
	(1.8793)	(1.5721)
Caregiver level of education	2.5112*	-1.1096
Primary school	(1.2686)	(1.3441)
Junior middle school	5.5667***	1.4832
	(1.2349)	(1.4922)
Senior middle school	7.7830***	2.1552
	(1.5217)	(1.8226)
Vocational school	14.6363***	1.9270
	(1.8635)	(2.0499)
University and above	6.0638*	-1.6722
	(3.2995)	(3.8058)
Mom was at home taking care of the child	1.1709	-0.9154
	(0.7195)	(0.7876)
Household income (in 1000 yuan)	0.0351***	0.0448***
	(0.0122)	(0.0123)
Number of days air temperature ≥ 25℃	-0.0263	0.0085
	(0.0317)	(0.0359)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5751	5735

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early

language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 8: A subsample of mom took care of her child at home.

	MDI	PDI
$PM_{2.5}$ in first trimester	-0.0630	-0.0144
	(0.0476)	(0.0447)
$PM_{2.5}$ in second trimester	-0.1116**	-0.1796***
	(0.0489)	(0.0403)
$PM_{2.5}$ in third trimester	-0.0154	0.0882
	(0.0536)	(0.0552)
$PM_{2.5}$ from born to survey	-0.3478***	-0.9409***
	(0.1110)	(0.1105)
Child months of age	-0.5308***	-0.1486**
	(0.1949)	(0.4011)
Child is male	-2.0651***	-0.8742
	(0.7033)	(0.5849)
Breastfed only	-0.1712	1.2371
	(1.9044)	(1.6803)
Caregiver level of education	2.7596	0.9078
Primary school	(1.9492)	(1.8331)
Junior middle school	6.5122***	3.6237*
	(1.8756)	(1.9795)
Senior middle school	9.0074***	4.1801*
	(2.2781)	(2.3974)
Vocational school	15.9767***	5.9959**
	(2.6355)	(2.4610)
University and above	5.1521***	2.5077
	(3.5728)	(5.1516)
Household income (in 1000 yuan)	0.0176	0.0416***
	(0.0148)	(0.0149)
Number of days air temperature ≥ 25℃	-0.0221	0.0067
	(0.0395)	(0.0378)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	4265	4252

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 9: Moderation effects & a subsample of mom took care of her child at home.

	MDI	PDI
MNP	3.3958	-0.4863
	(4.4545)	(4.8054)
$PM_{2.5}$ in first trimester	-0.0263	-0.0419
	(0.0547)	(0.0689)
MNP* $PM_{2.5}$ in first trimester	-0.0619	0.0369
	(0.0631)	(0.0752)
$PM_{2.5}$ in second trimester	-0.1850***	-0.2558***
	(0.0502)	(0.0437)
MNP* $PM_{2.5}$ in second trimester	0.1169***	0.1187***
	(0.0353)	(0.0404)
$PM_{2.5}$ in third trimester	0.0005	-0.1375*
	(0.0572)	(0.0725)
MNP* $PM_{2.5}$ in third trimester	-0.0259	0.0702*
	(0.0600)	(0.0588)
$PM_{2.5}$ from born to survey	-0.2773**	-0.8110***
	(0.1270)	(0.1386)
MNP* $PM_{2.5}$ from born to survey	-0.1038	-0.2006
	(0.1223)	(0.1500)
Child months of age	-0.5427***	-0.1587
	(0.1990)	(0.4045)
Child is male	-2.036***	-0.8795
	(0.7018)	(0.5829)
Breastfed only	-1.2763	1.1527
	(1.8500)	(1.6145)
Caregiver level of education	3.0495	1.1390
Primary school	(1.9943)	(1.8280)
Junior middle school	6.7636***	3.7966
	(1.8974)	(1.9664)
Senior middle school	9.3887***	4.5413
	(2.3173)	(2.4328)
Vocational school	16.2077***	6.0750
	(2.6589)	(2.4655)
University and above	5.7073***	3.1969
	(3.6949)	(5.1861)
Household income (in 1000 yuan)	0.0172**	0.0404***
	(0.0147)	(0.0145)
Number of days air temperature ≥ 25℃	-0.0200	0.0087
	(0.0390)	(0.0379)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	4265	4252

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 10: AQI.

	AQI 50		AQI 100	
	MDI	PDI	MDI	PDI
Number of days in first trimester	-0.0027	-0.0002	-0.1365***	-0.0927***
	(0.0345)	(0.0384)	(0.0344)	(0.0328)
Number of days in second trimester	-0.0761**	-0.1208***	-0.1439***	-0.2093***
	(0.0287)	(0.223)	(0.0445)	(0.0320)
Number of days in third trimester	0.0453	-0.0087	-0.0339	-0.1046**
	(0.0324)	(0.0407)	(0.0418)	(0.0449)
Number of days from born to survey	-0.0078	-0.0728***	-0.0197	-0.1870***
	(0.0150)	(0.0136)	(0.0400)	(0.0335)
Child months of age	-0.3403	0.7555*	-0.3463	0.5229
	(0.2689)	(0.3956)	(0.2004)	(0.3786)
Child is male	-2.3716***	-0.7558	-2.3390***	-0.7931
	(0.5250)	(0.4944)	(0.5215)	(0.4921)
Breastfed only	-1.7282	-0.7641	-1.4098	-0.5206
	(2.0228)	(1.8622)	(1.9605)	(1.7487)
Caregiver level of education	2.3045*	-1.1986	2.4706*	-1.1385
Primary school	(1.2452)	(1. 3988)	(1.2533)	(1.3812)
Junior middle school	5.4542***	1.4704	5.5819***	1.5349
	(1.2319)	(1. 5375)	(1.2129)	(1.4971)
Senior middle school	7.6802***	2.1406	7.7039***	2.0582
	(1.5276)	(1.8317)	(1.4807)	(1.7844)
Vocational school	14.6852***	2.3504	14.7950***	2.2802
	(1.8621)	(2.0477)	(1.8655)	(2.0297)
University and above	6.0721*	-1.8411	6.1573*	-2.0153
	(3.3711)	(3.8201)	(3.3008)	(3.7944)
Mom was at home taking care of the child	1.2394*	-0.8330	1.2238*	-0.8240
	(0.7068)	(0.7962)	(0.7034)	(0.7895)
Household income (in 1000 yuan)	0.0351***	0.0449***	0.0352***	0.0449***
	(0.0124)	(0.0130)	(0.0122)	(0.0128)
Number of days air temperature ≥ 25℃	-0.0410	-0.0001	-0.0037	0.0359
	(0.0417)	(0.0392)	(0.0298)	(0.0338)
Wave fixed effects	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
Observations	5753	5737	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 11: Moderation effects & AQI.

	AQI 50		AQI 100	
	MDI	PDI	MDI	PDI
MNP	-0.8266	0.1452	-0.1595	0.4633
	(2.1947)	(2.7574)	(1.0845)	(1.4296)
Number of days in first trimester	0.0126	0.0243	-0.0971	-0.0500
	(0.0356)	(0.0422)	(0.0403)	(0.0444)
MNP*Number of days in first trimester	-0.0220	-0.0412	-0.0609	-0.0695
	(0.0269)	(0.0287)	(0.0426)	(0.0537)
Number of days in second trimester	-0.1005***	-0.1477***	-0.1857***	-0.2694***
	(0.0291)	(0.0241)	(0.0493)	(0.0351)
MNP*Number of days in second trimester	0.0383**	0.0444**	0.0629*	0.0945***
	(0.0179)	(0.0180)	(0.0364)	(0.0352)
Number of days in third trimester	0.0624*	-0.0156	-0.0093	-0.1192**
	(0.0347)	(0.0434)	(0.0538)	(0.0566)
MNP*Number of days in third trimester	-0.0244	0.0086	-0.0347	0.0231
	(0.0263)	(0.0236)	(0.0485)	(0.0513)
Number of days from born to survey	-0.0109	-0.0716***	-0.0275	-0.1772***
	(0.0153)	(0.0139)	(0.0408)	(0.0344)
MNP*Number of days from born to survey	0.0047	-0.0015	0.0120	-0.0142
	(0.0039)	(0.0052)	(0.0127)	(0.0180)
Child months of age	-0.3334	0.7524*	-0.3457*	0.5193
	(0.2691)	(0.3960)	(0.2006)	(0.3789)
Child is male	-2.3553***	-0.7968	-2.3330***	-0.8050
	(0.5257)	(0.4883)	(0.5209)	(0.4860)
Breastfed only	-1.7991	-0.8352	-1.4930	-0.6033
	(2.0116)	(1.8459)	(1.9360)	(1.7120)
Caregiver level of education				
Primary school	2.4310*	-1.1814	2.5575**	-1.0389
	(1.2684)	(1. 3840)	(1.2710)	(1.3607)
Junior middle school	5.5350***	1.4571	5.6100***	1.5850
	(1.2488)	(1. 5318)	(1.2311)	(1.4911)
Senior middle school	7.8238***	2.1580	7.7795***	2.1700
	(1.5391)	(1.8593)	(1.5049)	(1.8108)
Vocational school	14.7663***	2.1677	14.7646***	2.1792
	(1.8829)	(2.0409)	(1.8905)	(2.0170)
University and above	6.1194*	-1.7890	6.1881*	-1.8451
	(3.38421)	(3.8589)	(3.3180)	(3.8106)
Mom was at home taking care of the child	1.2651*	-0.8704	1.2443*	-0.8618
	(0.7109)	(0.7991)	(0.7047)	(0.7845)
Household income (in 1000 yuan)	0.0345***	0.0442***	0.0349***	0.0447***
	(0.0123)	(0.0129)	(0.0122)	(0.0128)
Number of days air temperature ≥ 25℃	-0.0409	0.0030	-0.0044	0.0369
	(0.0418)	(0.0394)	(0.0295)	(0.0337)
Wave fixed effects	Yes	Yes	Yes	Yes
County fixed effects	Yes	Yes	Yes	Yes
Observations	5753	5737	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early

language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 12: Impairment.

	MDI impairment	PDI impairment
$PM_{2.5}$ in first trimester	0.0016*	0.0004
	(0.0008)	(0.0009)
$PM_{2.5}$ in second trimester	0.0030***	0.0023***
	(0.0009)	(0.0009)
$PM_{2.5}$ in third trimester	0.0013	0.0016
	(0.0009)	(0.0011)
$PM_{2.5}$ from born to survey	0.0072***	0.0137***
	(0.0022)	(0.0025)
Child months of age	0.0137***	0.0090**
	(0.0040)	(0.0062)
Child is male	0.0366***	0.0130
	(0.0106)	(0.0114)
Breastfed only	-0.0020	-0.0221
	(0.0403)	(0.0496)
Caregiver level of education	-0.0522*	-0.0166
Primary school	(0.0267)	(0.0249)
Junior middle school	-0.1055***	-0.0429
	(0.0278)	(0.0278)
Senior middle school	-0.1553***	-0.0573*
	(0.0370)	(0.0308)
Vocational school	-0.2219***	-0.0736**
	(0.0395)	(0.0348)
University and above	-0.1467**	0.0537
	(0.0622)	(0.0684)
Mom was at home taking care of the child	-0.0019	0.0006
	(0.0170)	(0.0136)
Household income (in 1000 yuan)	-0.0004*	-0.0005**
	(0.0002)	(0.0002)
Number of days air temperature ≥ 25℃	0.0006	-0.0002
	(0.0007)	(0.0009)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 13: Moderation effects & impairment.

	MDI impairment	PDI impairment
MNP	-0.0731	0.0129
	(0.0817)	(0.0733)
$PM_{2.5}$ in first trimester	0.0019**	-0.0004
	(0.0009)	(0.0011)
MNP* $PM_{2.5}$ in first trimester	-0.0005	0.0013
	(0.0011)	(0.0010)
$PM_{2.5}$ in second trimester	0.0038***	0.0034***
	(0.0011)	(0.0009)
MNP* $PM_{2.5}$ in second trimester	-0.0013*	-0.0016***
	(0.0007)	(0.0006)
$PM_{2.5}$ in third trimester	0.0013	0.0014
	(0.0011)	(0.0013)
MNP* $PM_{2.5}$ in third trimester	-0.0000	0.0003
	(0.0011)	(0.0008)
$PM_{2.5}$ from born to survey	0.0051**	0.0140***
	(0.0024)	(0.029)
MNP* $PM_{2.5}$ from born to survey	0.0032	-0.0005
	(0.0019)	(0.0020)
Child months of age	0.0135***	0.0091
	(0.0040)	(0.0062)
Child is male	0.0369***	0.0131
	(0.0106)	(0.0112)
Breastfed only	-0.0015	-0.0202
	(0.0399)	(0.0491)
Caregiver level of education	-0.0528*	-0.0186
Primary school	(0.0264)	(0.0254)
Junior middle school	-0.1056***	-0.0436
	(0.0275)	(0.0281)
Senior middle school	-0.1572***	-0.0591*
	(0.0366)	(0.0315)
Vocational school	-0.2234***	-0.0719**
	(0.0389)	(0.0352)
University and above	-0.1488**	0.0518
	(0.0627)	(0.0684)
Mom was at home taking care of the child	-0.0018	0.0009
	(0.0172)	(0.0137)
Household income (in 1000 yuan)	-0.0004*	-0.0005**
	(0.0002)	(0.0002)
Number of days air temperature ≥ 25℃	0.0006	-0.0002
	(0.0007)	(0.0009)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early

language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 14: One year before 3-month preconception.

	MDI	PDI
$PM_{2.5}$ in first trimester	-0.0894*	-0.0374
	(0.0433)	(0.0411)
$PM_{2.5}$ in second trimester	-0.1470***	-0.1778***
	(0.0410)	(0.0282)
$PM_{2.5}$ in third trimester	-0.0433	-0.0835
	(0.0431)	(0.0528)
$PM_{2.5}$ from born to survey	-0.3770***	-0.9326***
	(0.1126)	(0.1128)
$PM_{2.5}$ one year before 3-month conception	-0.1344	0.7432
	(0.3687)	(0.6695)
Child months of age	-0.5042***	-0.1009
	(0.1813)	(0.3282)
Child is male	-2.3805***	-0.7879
	(0.5211)	(0.4977)
Breastfed only	-0.5857	1.5633
	(1.9039)	(1.6410)
Caregiver level of education	2.3590*	-1.1726
Primary school	(1.2466)	(1.3558)
Junior middle school	5.4554***	1.4946
	(1.2201)	(1.4870)
Senior middle school	7.6136***	2.0659
	(1.5154)	(1.7929)
Vocational school	14.5317***	2.0222
	(1.8548)	(2.0541)
University and above	5.9705*	-1.7722
	(3.2899)	(3.7768)
Mom was at home taking care of the child	1.1631	-0.8711
	(0.7103)	(0.7800)
Household income (in 1000 yuan)	0.0356***	0.0453***
	(0.0122)	(0.0126)
Number of days air temperature ≥ 25℃	-0.0291*	0.0242
	(0.0360)	(0.0329)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 15: Moderation effects & one year before 3-month preconception.

	MDI	PDI
MNP	1.9989	2.1520
	(3.2771)	(4.1657)
$PM_{2.5}$ in first trimester	-0.0729	-0.0263
	(0.0466)	(0.0592)
MNP* $PM_{2.5}$ in first trimester	-0.0259	-0.0221
	(0.0428)	(0.0612)
$PM_{2.5}$ in second trimester	-0.1898***	-0.2331***
	(0.0433)	(0.0318)
MNP* $PM_{2.5}$ in second trimester	0.0684**	0.0898***
	(0.0312)	(0.0321)
$PM_{2.5}$ in third trimester	-0.0201	-0.1113*
	(0.0502)	(0.0660)
MNP* $PM_{2.5}$ in third trimester	-0.0320	0.0411
	(0.0443)	(0.0475)
$PM_{2.5}$ from born to survey	-0.3377***	-0.8287***
	(0.1201)	(0.1287)
MNP* $PM_{2.5}$ from born to survey	-0.0550	-0.1566
	(0.0897)	(0.1334)
$PM_{2.5}$ one year before 3-month conception	-0.0890	0.7653
	(0.3707)	(0.6708)
Child months of age	-0.4926**	-0.0992
	(0.1846)	(0.3305)
Child is male	-2.36468***	0.8074
	(0.5220)	(0.4938)
Breastfed only	-0.6457	1.4704
	(1.8811)	(1.5812)
Caregiver level of education	2.5078*	-1.0819
Primary school	(1.2681)	(1.3409)
Junior middle school	5.5595***	1.5426
	(1.2336)	(1.4803)
Senior middle school	7.7802***	2.1771
	(1.5211)	(1.8179)
Vocational school	14.6336***	1.9481
	(1.8627)	(2.0575)
University and above	6.0533*	-1.5831
	(3.2910)	(3.8134)
Mom was at home taking care of the child	1.1704	-0.9120
	(0.7193)	(0.7822)
Household income (in 1000 yuan)	0.0352***	0.0446***
	(0.0122)	(0.0124)
Number of days air temperature ≥ 25℃	-0.0280	0.0269
	(0.0360)	(0.0332)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by

adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 16: Birth season.

	MDI	PDI
$PM_{2.5}$ in first trimester	-0.1020**	-0.0140
	(0.0461)	(0.0484)
$PM_{2.5}$ in second trimester	-0.1620***	-0.1747***
	(0.0455)	(0.0504)
$PM_{2.5}$ in third trimester	-0.0799*	-0.0299
	(0.0440)	(0.0573)
$PM_{2.5}$ from born to survey	-0.3702***	-0.9613***
	(0.1098)	(0.1131)
Child months of age	-0.5250***	-0.1296
	(0.1864)	(0.3153)
Child is male	-2.3825***	-0.8036
	(0.5167)	(0.4930)
Child birth season		
Summer	-1.1683	2.0286*
	(1.0353)	(1.0382)
Fall	-1.6146	2.5145*
	(1.1069)	(1.1964)
Winter	-1.1562	1.5766
	(1.2226)	(1.2979)
Breastfed only	-0.5755	1.5006
	(1.8995)	(1.6108)
Caregiver level of education	2.2869*	-1.0824
Primary school	(1.2338)	(1.3532)
Junior middle school	5.3903***	1.5462
	(1.2182)	(1.5004)
Senior middle school	7.5587***	2.1320
	(1.5148)	(1.8058)
Vocational school	14.4039***	2.2016
	(1.8353)	(2.0516)
University and above	5.9869*	-1.8551
	(3.3116)	(3.7588)
Mom was at home taking care of the child	1.1612	-0.8613
	(0.7119)	(0.7851)
Household income (in 1000 yuan)	0.0358***	0.0451***
	(0.0123)	(0.0125)
Number of days air temperature ≥ 25℃	-0.0245	0.0048
	(0.0356)	(0.0345)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature ≥ 25℃. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1

Table 17: Moderation effects & birth season.

	MDI	PDI
MNP	1.9536	2.1801
	(3.3269)	(4.1645)
$PM_{2.5}$ in first trimester	-0.0854*	-0.0050
	(0.0504)	(0.0629)
MNP* $PM_{2.5}$ in first trimester	-0.0276	-0.0173
	(0.0427)	(0.0617)
$PM_{2.5}$ in second trimester	-0.2077***	-0.2263***
	(0.0474)	(0.0528)
MNP* $PM_{2.5}$ in second trimester	0.0692**	0.0858***
	(0.0311)	(0.0316)
$PM_{2.5}$ in third trimester	-0.0561	-0.0618
	(0.0518)	(0.0688)
MNP* $PM_{2.5}$ in third trimester	-0.0348	0.0495
	(0.0443)	(0.0479)
$PM_{2.5}$ from born to survey	-0.3352***	-0.8527***
	(0.1171)	(0.1261)
MNP* $PM_{2.5}$ from born to survey	-0.0503	-0.1660
	(0.0902)	(0.1341)
Child months of age	-0.5219***	-0.1300
	(0.1892)	(0.3174)
Child is male	-2.3666***	-0.8281
	(1.8768)	(0.4889)
Child birth season		
Summer	-1.1682	2.0644
	(1.0297)	(1.0257)
Fall	-1.6221	2.6086
	(1.0987)	(1.1875)
Winter	-1.2285	1.6540
	(1.2270)	(1.2903)
Caregiver level of education	2.4345*	-1.0066
Primary school	(1.2555)	(1.3406)
Junior middle school	5.4901***	1.5838
	(1.2316)	(1.4970)
Senior middle school	7.7252***	2.2291
	(1.5212)	(1.8319)
Vocational school	14.5042***	2.1186
	(1.8411)	(2.0579)
University and above	6.0663*	-1.6648
	(3.3137)	(3.7951)
Mom was at home taking care of the child	1.1706	-0.9071
	(0.7213)	(0.7886)
Household income (in 1000 yuan)	0.0355***	0.0444***
	(0.0122)	(0.0123)
Number of days air temperature ≥ 25℃	-0.0243	0.0070
	(0.0355)	(0.0348)
Wave fixed effects	Yes	Yes
County fixed effects	Yes	Yes
Observations	5753	5737

Notes: All regression control for child gender, child months of age, if the child was breastfed only, caregiver's level of education, whether the mother was at home taking care of the child, household income, and number of days when air temperature $\geq 25℃$. All standard errors are clustered on the county to allow for county-specific correlated errors over time. In both columns, I restrict the model by adding wave fixed effects and county fixed effects. Mental Developmental Index (MDI) assesses cognition through evaluation of sensory-perception, knowledge, memory, problem-solving, and early language. Psychomotor Developmental Index (PDI) assesses gross motor skills (e.g., crawling and walking), and fine motor skills (e.g., picking up objects between the thumb and finger).
*** p<0.01, ** p<0.05, * p<0.1