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DISCUSSION PAPER SERIES

IZA DP No. 16322

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ABSTRACT

Air Pollution and Education Investment*

Our study focuses on exploring the impact of air pollution on household investment in children's education in China. Air pollution poses a significant risk to some cities in northern China. We have used panel data from secondary schools in Shandong Province in 2017 and 2020 and discovered that a rise of one standard deviation of PM2.5 leads to a 9.6-44.6 percentage point decrease in the likelihood of parents spending on their children's education. The impact of air pollution on household education investment is mediated by parents' and children's educational expectations and household incomes. Our findings also indicate that high school students are more likely to receive higher education investment than middle school students, even at the same level of air pollution. The results of our study suggest that air pollution can lead to a decrease in human capital accumulation due to changes in parental behaviors induced by air pollution.

JEL Classification: Q53, I20, D10
Keywords: air pollution, education investment, China

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1. Introduction

The investment that households make in education plays a critical role in the future of their children. Education can be seen as both a consumption good and an investment that can bring benefits and well-being to both children and parents. Typically, it is the primary caregiver, such as the parent, who makes the household investments in education rather than the primary beneficiary, which is the child (Alderman and King, 1998), this is because the main function of the family is to produce and socialize children (Parcel et al., 2010). According to child development theory, family investment is crucial. The home environment is the first setting where children develop, and the family's influence on educational decisions may be more significant than school quality or teaching experience (Brown, 2006; Zhang, 2021). Attributes formed during childhood are crucial for adult outcomes (Francesconi and Heckman, 2016; Huggett et al., 2011). For example, several studies have indicated that around 60% of the variations in personal income are attributable to individual characteristics before adulthood (i.e., initial conditions) (Cunha et al., 2005).

Numerous studies have investigated the link between air pollution and health consequences, as well as academic achievement. Scientific investigations have revealed the substantial influence of airborne particulate matter on human health, including respiratory and metabolic illnesses (Chay and Greenstone, 2003; Deryugina et al., 2019), and shows strong evidence for the effects of air pollution on cognitive performance (Ebenstein et al., 2016). Air pollution can have both short-term and long-term effects on individuals. Studies in economics suggest that air pollution can impact people's behaviors and performance. For example, exposure to air pollution can cause negative emotions and lead to incorrect investment decisions, which can ultimately result in decreased work efficiency, lower academic performance, and reduced income (Borgschulte et al., 2022; Buoli et al., 2018; Chang et al., 2019; Shuai Chen et al., 2018; Graff Zivin and Neidell, 2012; Hanna and Oliva, 2015). Air pollution has had a significant negative impact on both the sustainable development of human society and the continuous growth of human capital.

Air pollution can lead to negative emotions such as pessimism and poor judgment, which can influence investors' behavior and cause them to be hesitant to hold stocks. This can ultimately impact the profitability of the stock market. Furthermore, recent research suggests that air pollution can also decrease an individual's confidence, leading to potential implications for their employment choices. As educational choices can significantly impact future job prospects, our study investigates whether air pollution also affects the accumulation of human capital in individuals prior to entering the workforce. Current literature has only examined the direct impact of air pollution on cognition and there is a lack of research on the influence of air pollution on educational choices (Graff Zivin et al., 2020). From a psychological perspective, we hypothesize that air pollution could impact educational choices. As parents are typically the main financial supporters of their children until college, we were interested in exploring whether air pollution could also affect a child's education from the perspective of parents. Parental educational investment is a crucial factor that contributes to the differences between socioeconomic and ethnic groups in terms of education, making it an important aspect to consider (Cheadle, 2008).

We situate our study in China for several reasons. First, the Chinese central government launched a rapid expansion program for the higher and further education sector in 1999 in order to stimulate domestic demand, boost GDP, and alleviate employment pressure (Yao, 2019). Second, Research has shown that Chinese parents place a high value on their children's education and are increasingly investing in it. They often prioritize spending on education and hope that their children can improve their living conditions by achieving high scores on exams and gaining admission to prestigious universities (H. Wang et al., 2022). China's total education spending has grown by approximately 30% from 2010 to 2018 (Wang and Cheng, 2021). Finally, air pollution levels in China vary significantly across regions, and the air pollution problem has remained severe in recent years. While the implementation of environmental policies has led to a decrease in air pollution levels in some parts of the country, the annual average concentrations of PM2.5 and PM10 in many major cities still surpass China's secondary standards for ambient air quality (i.e., 35 μg/m^3 for annual mean PM2.5 and 70 μg/m^3 for annual mean PM10). Moreover, the ongoing challenge for policymakers is due to the lack of public participation in social governance and the increase in average annual concentrations of other types of pollutants, such as ozone (Huang et al., 2018, 2018; Li et al., 2018; Zhu et al., 2022).

We employ an instrumental variable approach based on thermal inversions-induced air pollution to examine the causal impact of air pollution on parental educational investment among high school students. To do so, we match the 2017 and 2020 Database of Youth Health (DYH) collected in Shandong province with three datasets; namely, (1) high-resolution satellite air pollution data, which is based on 0.1 × 0.1 gridded estimates, collected by the National Aeronautics and Space Administration (NASA) in the United States; (2) NASA weather data, which is also based on 0.1 × 0.1 gridded estimates; and (3) city characteristics from the China City Statistical Yearbooks and the official documents of relevant city government agencies.

Our research indicates that PM2.5 exposure can result in a 9.5% decrease in educational engagement behavior, and this finding remained robust even after conducting additional tests. Additionally, the effects of particulate matter exposure cannot be attributed to the presence of greenhouse gases like ozone. We also found that air pollution is linked to a decline in the intensity of educational inputs and other inputs associated with the accumulation of children's human capital. Moreover, air pollution impacts educational investment via educational expectations and household economic factors. Furthermore, we observed that, under the same level of air pollution, children in higher grades receive more education investment. Finally, we found that the negative effect of air pollution on education investment is correlated with education level and gender.

Our study makes significant contributions to the literature on environmental pollution and human capital investment in several ways. Firstly, we are the first to investigate how air pollution impacts household investment in their children's education. Secondly, we adopt a parental behavior perspective to explain how air pollution may affect an individual's academic level and adult outcomes, as opposed to the previously studied mechanisms of children's school absences, physical health, and mental health (Isen et al., 2017; Zhang et al., 2018). Our study complements the literature in the field of air pollution and human capital. Thirdly, we have provided detailed explanations of various possible channels and conducted tests to explore how air pollution affects parental education investment, which is crucial for a better understanding of how air pollution impacts investment behavior. Our study also identifies additional factors, beyond physiological and psychological attributes, that may contribute to air pollution-related investment behaviors (An et al., 2018; Levy and Yagil, 2011). Lastly, our study provides a new perspective on the intergenerational transmission of socioeconomic status by exploring the potential impact of air pollution. Our findings suggest that air pollution may play a significant role in the relationship between parental behavior and children's academic and career outcomes.

Our research has significant implications for both future research and broader public policy. One of the main implications is that air pollution is a critical environmental issue that requires immediate attention. According to our findings, pollution was responsible for about 9 million premature deaths in both 2015 and 2019, making it the largest environmental risk factor for diseases and premature deaths, with one in six deaths worldwide attributed to it. Despite some reductions in recent years due to poverty-related pollution such as indoor household and water pollution, deaths from outdoor ambient air pollution and toxic chemical pollution such as lead, have actually increased. Moreover, according to the World Health Organization (WHO), 99% of the global population breathes air that exceeds safe air quality limits set by the WHO guidelines (WHO, 2022a). Particulate matter, especially PM2.5, has the ability to infiltrate the respiratory system, blood vessels, heart, brain, and other organs, resulting in detrimental effects. Air pollution can also cause psychological distress such as having felt sad, nervous, restless, hopeless, worthless, or "that everything was an effort" (Sass et al., 2017) and low labor productivity (Adhvaryu et al., 2022; Chang et al., 2019; Graff Zivin and Neidell, 2012). Our research suggests that the current measures of the social cost of pollution are insufficient and underestimate the true impact of air pollution on individual behavioral choices, such as parents' investment in their children's human capital. Our study offers a new perspective on how air pollution affects the intergenerational transmission of socioeconomic status. Additionally, low- and middle-income countries are the most affected by air pollution, but its negative effects can extend beyond their borders. The impact of air pollution on physical health and human capital accumulation requires collective action beyond local boundaries. Moreover, air pollution is closely related to climate change, as the burning of fuels generates short-lived climate pollutants, including methane (a precursor to ozone) and black carbon (a component of PM2.5). Consequently, implementing policies that target air pollution can have multiple benefits for improving the human living environment, and the advantages of these policies will outweigh their costs (Fuller et al., 2022; WHO, 2022b). The rest of the paper is organized as follows.

2. Literature review

The relationship between air pollution exposure and human capital formation through the intergenerational impact of emotion is not fully understood. Research in the fields of psychology and behavioral economics suggests that environmental factors such as air pollution and climate change can evoke negative and pessimistic emotions. Air pollution has been linked to anxiety, sadness, depression, and risk aversion, which can influence investment judgments and psychological expectations. Research suggests that the emotional response to air pollution, such as caution and prudence, may lead to stock market investors and auditors being more risk-averse in their investment decisions, resulting in a reduction in earnings forecasts and an improvement in the quality of judgments. Specifically, auditors tend to express greater pessimism towards their clients' financial statements when air pollution levels are high (Chen et al., 2020). Moreover, air pollution can have negative impacts on various aspects of cognitive function such as attention, responsiveness, and cognitive ability to process information. As an environmental stressor, air pollution can lead to prejudice at work and counterproductive behaviors, ultimately resulting in reduced labor productivity and impaired judgment. The adverse health and psychological effects of air pollution can also influence the major decisions of individuals. Good health and human capital are crucial for individuals to make optimal decisions that are beneficial to them (Huang et al., 2020; Liu et al., 2021; Tan and Yan, 2021). Although risk aversion due to air pollution may lead to a reduction in high-risk investment behaviors, the opportunity cost of air pollution-induced misperceptions and poor decision-making may be greater, especially considering the importance of parental investment in their children's education. Educating children is often viewed as a personal responsibility, and investment in education is believed to have a crucial impact on the accumulation of children's future human capital. Previous research on migrant children in China has shown that parents' educational expectations are highly correlated with their children's future educational attainment, and educational investment plays a significant mediating role in this relationship, along with the positive effects of community and school conditions (Luo et al., 2022). Our study supports earlier research on the detrimental impacts of air pollution, which have been linked to decreased psychological well-being and impaired decision-making. These decisions can manifest in educational investment choices, highlighting the significant role of air pollution in the perpetuation of intergenerational socioeconomic disparities.

Our research has implications for the studies on social costs of air pollution and other factors that impact household investment in education. Air pollution can impact individual income in multiple ways. Firstly, the adverse health consequences of air pollution are substantial, which can increase the likelihood of reduced working hours and further loss of income and career opportunities (Liu et al., 2020). Exposure to air pollution and its impact on children's health can lead to parents reducing their working hours and income (Currie, 2009). Second, exposure to harmful substances in air pollution, such as ozone, particulate matter, and fine particulate matter, can harm cognitive abilities that are essential for tasks like focus, concentration, and critical thinking. As a result, this could have a negative impact on work productivity, leading to reduced labor market performance and earnings linked to performance (Chang et al., 2019; Graff Zivin and Neidell, 2012). Finally, it is worth noting that air pollution can also worsen poverty and inequality as different income groups may be exposed to it differently. In developed countries, air pollution levels may be particularly high in low-income communities (Finkelstein et al., 2003; Jbaily et al., 2022). In China, while there may be a positive relationship between air pollution and the socioeconomic status of residents due to the growth of urbanization and inadequate environmental regulation, individuals with higher socioeconomic status tend to take protective measures to mitigate the negative effects of air pollution. These measures may include living in areas farther away from polluting industries, utilizing their political influence to improve residential infrastructure and increase the implementation of pollution control measures, owning vehicles to minimize exposure during their daily commute, and using their financial resources to exclude low-income individuals from residing in cleaner communities. This inequality is also reflected in the living environment of people with urban and rural *hukou*. For example, in Jiangsu Province in China, despite adjusting for the fact that rural migrants typically work in industries with high levels of pollution, the urban areas where rural migrants reside still experience significant levels of air and water pollution (Schoolman and Ma, 2012). The inequality between individuals with different socioeconomic statuses is further exacerbated by the fact that rural migrants not only lack the same rights as urban residents but also have to endure harsh living conditions. It has been suggested by some studies that a short-term increase in air pollution may be linked to economic growth and personal income due to the production effects (Y. Wang et al., 2022), but it is negative in the long term (Liu et al., 2020). Some researchers argue that the relationship between air pollution and socioeconomic status may not be linear. However, in situations of severe air pollution, high health risks may prompt individuals with higher socioeconomic status to relocate, making air quality a crucial factor in their decision. Moreover, the adverse health effects linked to air pollution tend to decrease as socioeconomic status increases (Jiao et al., 2018).

Furthermore, the impact of family income and background on children's education investment is significant. Parents' income not only affects educational returns but also provides available resources that can be used to finance education. Research has shown that increases in household income are positively associated with increases in children's college enrollment rates (Acemoglu and Pischke, 2001). Air pollution can have a negative impact on parental income, as it can lead to increased healthcare costs and decreased work productivity. As a result, parents may face financial constraints that reduce their ability to invest in their children's education.

In addition, the relationship between air pollution and educational investment may be moderated by individual education and gender. Children in higher-grade levels may require more educational investment due to an increased number of subjects to learn and more complex learning content. At the same time, in China, compulsory education only covers junior high school education, and high school education is not included. Therefore, high school students may require more investment in education than junior high school students. Additionally, the government provides subsidies for tuition fees for junior high school education in most schools (Eryong and Xiuping, 2018). Moreover, studies have shown that in certain underdeveloped regions, girls may have fewer opportunities to receive an education due to traditional cultural beliefs surrounding family responsibilities and gender roles, as well as gender disparities in labor force participation and wages (Alderman and King, 1998). During the 1990s in rural China, children from impoverished families may have had to compete with their siblings for educational resources, and girls might have faced obstacles in receiving adequate education investment due to traditional patriarchal ideology, leading to early dropout rates. However, with the gradual decline of gender inequality and the implementation of the one-child policy in China, there may not be significant gender disparities in educational spending, expectations, and attainment of children (Hannum et al., 2009; Lee, 2012).

We acknowledge the relevance of a prior study on the association between air pollution and children's earnings in adulthood. This study compared birth cohorts in counties with varying levels of air pollution before and after the implementation of the Clean Air Act in 1970. The findings showed that early exposure to air pollution during childhood is linked to lower labor force participation rates and income levels at age 30. The study also suggests that air pollution has a greater impact on disadvantaged groups. It is possible that air pollution affects children in the long term through health capital, such as chronic diseases and weight, as well as cognitive and non-cognitive skills, which can be reflected in exam scores or other personality traits (Isen et al., 2017). However, the study primarily focuses on the impact of air pollution on education investment and only briefly mentions the potential reinforcing or compensatory role of parental education investment in children's human capital formation.

Our study adds to the existing literature on the impact of air pollution on human capital formation and intergenerational socioeconomic status transmission. Prior studies have consistently shown that air pollution has detrimental effects on the cognitive development and behaviors of children and parents (Siyu Chen et al., 2018; Evans and Jacobs, 1981; Huang et al., 2020). At the same time, Research suggests that there is a strong correlation between education, health capital, and economic conditions across generations, implying the existence of intergenerational persistence. Parents with lower financial resources often encounter difficulties in making substantial investments in their children's health and education, and their children inherit fewer assets (Cooper and Stewart, 2021). This disparity between economic and health status can span generations (Chakraborty and Das, 2005) and is rising in China (Fan et al., 2021). Our research aims to demonstrate that air pollution can influence the intergenerational transmission of socioeconomic status by affecting parental investment in education, which, in turn, may impact the accumulation of human capital in children.

3. Data

The final combined dataset includes data on secondary school students, air pollution, thermal inversions, weather and city characteristics from 2017 and 2020 in Shandong province in China. The 2017-2020 DYH survey was administrated by Shandong University among high school students (years 7-12). The DYH first randomly selected schools using a probability-proportional-to-size sampling and then randomly survey students in each selected school. (Zhang et al., 2022). The DYH surveyed 99,327 students from 186 high schools in 17 cities within Shandong province. The DYH collected information on students and parents and household education investment.

The data allow us to measure not only the education investment behaviors but also the related information of parents and children. Education investment behaviors are defined by whether the student attends after-school tutorial class (yes = 1). Receiving tutoring in addition to regular school instruction (i.e., shadow education) is prevalent in many developing countries due to the existence of high-stakes examinations and low-educated parents. It is a supplement to human capital formation outside the school (Jayachandran, 2014; Pan et al., 2022). We construct an adjusted education investment variable by using principal component analysis based on whether the student attends after-school tutorial class (yes = 1) and whether the student has many books (yes = 1). We include the book numbers at home measure since it is a part of the family's cultural resources and would foster children's reading motivation and written culture and enhance learning stimulation (Conger and Donnellan, 2007; Heppt et al., 2022).

Data on surface-level air pollution is taken from NASA, which might provide more accurate and reliable data than other air quality data from official monitors (e.g., official air pollution data might have potential manipulation problems due to promotion incentives of government officers (Qin and Zhu, 2018)). The satellite-based readings of NASA PM2.5 data with a spatial resolution of 0.1° × 0.1° are gathered from Global/Regional Estimates (V5.GL.02) from Washington University in St. Louis[1].

The information on thermal inversions and weather with a 0.1° × 0.1° spatial resolution is also obtained from NASA in order to ensure consistency of environmental data sources. The former is calculated based on an instantaneous 3-dimensional 6-hourly dataset and the latter is obtained from post-processed 3-hourly data, which corrected previous grid box issues and was updated in October 2020.[2]

We also collect city-level attribute data from China City Statistical Yearbook and local government websites. We merge the survey data with the city characteristics data by city and year. we assign the air pollution, thermal inversions and weather data with the closest latitude and longitude to the given city.

Insert Table 1 about here

The combined dataset consists of 32094 students in 10 cities in Shandong province in 2017 and 2020. There are 19808 middle school students and 12286 high school students, 48.8% of them are females and 51.2% of them are males. Table 1 displays summary statistics for the full sample and sub-group sample across education levels and gender. We observe that 58.3% of students receive parental education investment. We also observe that middle school students have a relatively low level of parental education investment than high school students. Females tend to have a higher possibility of receiving education investment than males. We also report Welch's t-statistics of our sample to estimate the differences between middle school and high school students as well as females and males. The Welch's t-statistics indicate significant disparities between middle school and high school students as well as between the females and the males: middle school students and females tend to have less education investment and the yearly mean PM2.5 is lower for the females than for the males.

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[1] The data could be accessed from the website: https://sites.wustl.edu/acag/datasets/surface-pm2-5/.

[2] Thermal inversions data is obtained from https://disc.gsfc.nasa.gov/datasets/M2I6NPANA_5.12.4/summary?keywords=m216npana, and weather data is gathered at https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_3H_2.1/summary.

4. Model and identification

We use fixed effects model and instrumental variable strategy to overcome potential endogeneity issues for inferring the causal relationship between air pollution and education investment. The education investment might be low in poor areas with high air pollution and the impact of air pollution might be overstated (Bondy et al., 2020). We construct the following model to identify the link between air pollution and education investment:

$$I\_edu_{i,j,t} = \alpha_0 P_{i,j,t} + X_{i,j,t} + \gamma_j + \delta_t + \varepsilon_{i,j,t} \quad (1)$$

where $I\_edu_{i,j,t}$ is the education investment of individual i in city j in year t and $P_{j,t}$ is PM2.5 concentrations of individual i in city j in year t. PM2.5 is instrumented by the predicted value of PM2.5 to address the endogeneity problem of air pollution arising from sorting problems, air pollution avoidance behaviors and the relationship between air pollution and local economic activities. The predicted PM2.5 is based on the value of thermal inversions, wind speed, wind direction, and the number of occurrences of temperature inversions.[3] $X_{i,j,t}$ is a vector of individual- and city-level covariates. γ_j, δ_t and $\varepsilon_{i,j,t}$ represent city fixed effect, year fixed effect and standard errors, respectively.

Education investment, emotions and related behaviors might be correlated with time-varying and time-invariant characteristics. We control for these covariates in order to obtain correct estimates. We control for personal characteristics such as age, age squared, whether male (yes = 1), whether han nationality (yes = 1), hukou status (other status = 1, rural = 2, urban = 3), whether live in city (yes = 1), whether migrant (yes = 1), education level of children (middle school = 0, high school = 1), whether key classes (yes = 1), whether leader (yes = 1), whether one-child family (yes = 1), parents' education level (i.e., highest level of education attended by parents, below university = 0, university or above = 1). For city-level attributes, we include real gross domestic product per capita (thousand yuan), population density (per km^2), ground-level temperature (°C), number of industrial firms per capita, thermal power plants effects (i.e., the distance-weighted electric energy production of thermal power plants within 200 kilometers) and forests effects (i.e., i.e., distance-weighted areas of forests within 200 kilometers).

We include year fixed effect to control for common trends across years and absorb common year-specific shocks (Grossmann et al., 2021). We allow for city fixed effects to account for any confounding from time-invariant structural differences between cities. Also, in our model, the error term is clustered at the city to address the concern that standard errors among students within the same city are positively correlated (i.e., unobserved within-city correlations arising) and might result in false significance.

Moreover, we conduct a three-step approach to test the mediator roles of parent education expectation, child education expectation and household income level (Baron and Kenny, 1986) and add interactions to measure the moderator roles of education level and gender. We also perform several robustness checks to confirm that the results are not confounded by other variables related to education investment.

[3] Temperature differences are calculated based on layers from 1000-975 and 975-950 hPa .

5. Results

We first present the coefficient estimates of education investment models. Second, we explore the mechanisms through which air pollution affects education investment. Next, we measure the moderating effects. Lastly, we show a series of robustness tests. All of the models include controls, city fixed effect and year fixed effect.

Insert Table 2 about here

Table 2 displays the impacts of air pollution on three types of education investment based on the estimation of Equation (1). The models in Column (1) adopt OLS method and the models in Column (2) utilize the Two-Stage least squares (2SLS) method. The 2SLS results show that the coefficient estimates on PM2.5 are negative and significant in all columns. A unit (one standard deviation) increase in PM2.5 will lead to a 0.9-4.2% (9.6-44.6%) reduction in the possibility of receiving parental education investment. The t statistics and F statistics of the instrumental variable are greater than 3.43 and 10, respectively, indicating no weak instrument issues.

Insert Table 3 about here

Second, the results in Table 3 suggest that air pollution might have effects on education investment through several channels. Although the results of education investment in Panel A show that both parental education and child education expectation might play a full mediation role, there is a concern that the existence of two full mediators might contradict each other. The results of Column (3) in Panel A and adjusted education investment in Panel B indicate that parental education expectation, child education expectation and household income level are likely to partially mediate the relationship between air pollution and education investment.[4] n the first regressions of air pollution and education investment, if excluding individuals with missing mediators' information, the results are significant and negative. The second regressions further show that air pollution is significantly negatively associated with mediators. In the third regression, when including both air pollution and a mediator, the results show that the coefficients of air pollution and the mediator are significant. The coefficients of the air pollution have lower values than the coefficients of the independent variable in the first regression.

Insert Table 4 about here

[4] Although we found mediators might play full mediator roles in education investment regressions, the existence of three full mediators might indicate that the impacts of these mediators are only partial.

Third, we interact air pollution with education level and gender and present the results after adding interactions. In Table 4, there is a significant indication that the impact of air pollution on education investment is moderated by education level in the adjusted education investment regressions. The results show that high school students might have more education investment compared to their counterparts. The results also show non-significant results for a gender effect. Although females might receive less attention from parents in the old generation (due to social norms that value males over females), the current high women's social status might mitigate the negative circumstances for females. According to the 2019 report on Chinese Women's Development Outline (2011-20) from the Chinese National Bureau of Statistics, more females are in higher education, which will lead to increasing number of women in high-level jobs with high salaries (China Daily, 2020). Considering that moderation regressions are multivariate models with more than one explanatory variable, we test the degree of instrument relevance by utilizing Shea's partial R squared. We find strong Shea's partial R squared values of the interactions (i.e., larger than 0.7 is higher relevance)[5], which confirm the consistency of 2SLS estimates.

Insert Table A1 about here

Finally, we begin by conducting several robustness checks to address potential concerns. In Table A1, we use alternative measures of education investment as a dependent variable in the main regression. The dependent variables are adjusted education investment generated by principal component analysis. The first dependent variable is based on whether the student attends after-school tutorial class (yes = 1), whether the student has many books (yes = 1) and whether the student has a good relationship with parents (yes = 1). The second dependent variable is calculated from the number of after-school tutorial classes, a categorical variable representing the number of books at home (from 1 to 5, the higher the greater) and whether the student has a good relationship with parents (yes = 1). These two dependent variables measure the existence and the intensity of family relationship-adjusted education investment, respectively. The results are significant and negative, which is consistent with our previous main results in Table 2.

Insert Table A2 about here

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[5] A value between 0.5 and 0.7 indicate moderate effect and medium relevance. And a value below 0.5 is considered low relevance and might cause the finite-sample distribution of 2SLS estimation to depart sharply from the asymptotic normal distribution (Shea, 1997).

Considering air pollution might have lagged effects on education investment, we replicate the primary results adding average PM2.5 values in previous years. In Panel A of Table A2, we find that the coefficient estimates on previous PM2.5 are significant and negative in the previous 1 and 2 years in education investment and adjusted education investment regressions. The results also suggest significant and negative in the previous 3 years in adjusted education investment regression. After adding the PM2.5 value in current years, the coefficients become not significant. Although with the weak instrument of the current air pollution variable, the magnitude and direction of coefficients indicate that air pollution in previous years does not impact education investment significantly and negatively. In alternative words, the concurrent impact rather than the cumulative impact of air pollution might play a more important role in the changes in education investment behaviors.

Insert Table A3 about here

Our previous results show a linear relationship between air pollution and education investment. We next text for the non-linear impact of air pollution by inducing the squared term of air pollution. Table A3 displays the estimation results and indicates that the negative impact of air pollution on education investment behaviors will strengthen before the turning point is reached (i.e., 47.5 $\mu g/m^3$ for education investment regression and 74.5 $\mu g/m^3$ for adjusted education investment regression) and the negative effects might be mitigated by other factors (e.g., immune adjustment of the human body and avoidance behaviors) after air pollution higher than turning point.

Insert Table A4 about here

In Table A4, we test the impact of other potential mechanisms. The coefficients of air pollution are not significant in the direct effect in Column (1), Column (2), Column (5), Column (6) and Column (7) in Panel A, indicating that we cannot confirm that air pollution will affect education investment via memory and school performance. In Column (3) and Column (4), the coefficients of air pollution and mediator in direct effects and mediating effects are significant, and the coefficients of air pollution are significant and become slightly lower than the coefficients in mediating effects regression after utilizing air pollution and mediators as independent variables. Moreover, the results in Panel B suggest that memory, parental study abroad expectation, child study abroad expectation and self-worth might play mediating roles in the correlation between air pollution and adjusted education investment. The full mediation effect of school performance is in line with current literature on air pollution and education outcomes (Isen et al., 2017) and might represent high relevance between air pollution and school performance. Our results indicate that air pollution will affect education investment through channels such as memory, parental and child study abroad expectations and self-worth.

Insert Table A5 about here

Table A5 displays the results of testing the moderation effect of grade and whether has a male child in the family. In Column (1) and Column (3), although the results of education investment regression show no significant results of air pollution and grade interaction, the interaction of air pollution and 3.grade (i.e., grade 10 or grade 11 in high school) is significant in adjusted education investment regression, which proves that the education investment of high school students might be more likely to be affected by air pollution. In Column (2) and Column (4), we focus on the female sample and see if a male child in the family will affect the female's education investment. The results are significant in education investment regression (i.e., females who live in a family with a male child might have more education investment) but not significant in adjusted education investment regression (i.e., females who live in a family with a male child might not affect their possibility of receiving parental investment in education). These findings confirm the consistency of our previous results.

Insert Table A6 about here

Our data gathered information from students who are living in urban areas and rural areas. Outdoor air pollution issues for rural residents are generally considered more important than for urban residents in China due to low levels of living standards and care services (Zhao et al., 2021). Yet, the lack of educational resources and paternal labor migration tendency might lead to low investment in education and continued low performance of students (Shen et al., 2021). Rural students might have very few opportunities to receive education investment, even in the absence of air pollution issues. Therefore, we expect to see that education investment behaviors in rural areas are not sensitive to air pollution. To test the hypothesis, we estimate the primary regression across living areas. The results presented in Table A6 suggest that the negative impacts of air pollution on education investment are significantly negative in urban areas, whereas they are not significant in rural areas.

Insert Table A7 about here

The highly controversial One-Child Policy in China implemented in 1979 led to an increase in many one-child families. Recent studies pointed out that being an only child might receive more attention from parents and are more likely to have a close relationship with parents (Liu and Jiang, 2021). After addressing endogenous issues (i.e., child number and education choices are subject to parental discretion and might be determined simultaneously), the smaller household size from an exogenous reduction in child quantity will increase the educational attainment of children (Huang, 2022). Although students who are living in a non-one-child family might be at a disadvantage when exposed to air pollution, the low education inputs from parents without the impact of air pollution might lead to a non-significant link between air pollution and education investment. The results displayed in Table A7 present that the negative impact of air pollution might be more important for students who are living in a one-child family.

Insert Table A8 about here

Our previous results indicate that education level might moderate the relationship between air pollution and education investment. We next conduct a sub-group analysis to check if air pollution exists for both middle school and high school students. Table A8 displays the estimation results. The coefficient of PM2.5 is statistically significant for both middle school and high school students in the adjusted education investment regression. Our results suggest that although education level might play a moderate role, all students in secondary schools are experienced the negative impact of air pollution.

Insert Table A9 about here

In Table A9, we conduct a sub-group analysis according to the graduation cohort. Students who are in graduation cohorts (i.e., grade 9 in middle school and grade 12 in high school) are preparing for the high school or university entrance examinations, which is a key prerequisite for students to attend higher education level. They might face challenges and receive more attention and investment from parents and might not be sensitive to the impact of air pollution, and they tend to participate in shadow education due to peer effects (i.e., long exposure time with classmates) (Pan et al., 2022). The results show that the negative impact of air pollution on education investment is not significant for the graduation cohort and significant for the non-graduation cohort, which prove the correctness of our assumption.

Insert Table A10 about here

We employ the (Oster, 2019) test in Table A10 to further test the importance of selection on unobservables. We generate a predicted PM2.5 based on the first step of the 2SLS regressions of education investment and adjusted education investment, and we calculate the delta value based on the beta value of the 2SLS estimate. Next, we run the second step of the 2SLS regressions and compute the bound of the set with the calculated delta value (Ciacci, 2021). Results suggest that the beta coefficients without and with controls are negative and significant. The bias-adjusted beta coefficients on education investment and adjusted education investment are also negative and are at a similar magnitude compared to the controlled effect beta (the bounds of the set do not include zero and between the +/- 2.8 standard errors of the controlled estimates).

6. Results

This study utilizes a student dataset to observe education investment behaviors and identify the impact of air pollution on education investment. We include air pollution and weather data from NASA as well as city-level characteristics from government websites. Our identification strategy employs an instrumental variable method and a two-dimensional fixed effect model. The main findings show that a one standard deviation increase in PM2.5 will lead to a 9.6%-44.6% reduction in the possibility of receiving education investment. Additionally, our findings show that the association is influenced by parental education expectations, child education expectations, and household income levels. We also examined the moderating effects of education levels and gender, and found that high school students tend to receive more investment in education. These results indicate a potential cost of air pollution that is currently overlooked in policy discussions. Policymakers have the ability to shape and regulate air quality. Furthermore, not accounting for the role of parents in the long-term effects of air pollution on children's outcomes in adulthood may result in a significant underestimation of the impact of air pollution.

Although our findings have passed several tests, it is crucial to acknowledge some possible limitations. Firstly, other factors may affect the investment in education, and we should investigate other possible explanations for our results. Secondly, we need to distinguish how air pollution affects education investment before, during, and after the turning point of air pollution. The negative impact of air pollution may differ in these different periods. Lastly, it would be worthwhile to explore the association between air pollution and other forms of investment behaviors in future studies.

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TABLE 1
Descriptive Statistics

Panel A. Education level

Variables	Full sample		Middle school		High school		Welch's t-statistic
	Mean	SD	Mean	SD	Mean	SD	
Education investment (yes = 1)	0.583	0.493	0.506	0.500	0.707	0.455	-37.181***
Adjusted education investment	0.011	1.048	-0.084	1.064	0.163	1.002	-20.986***
PM2.5 (μg/m^3)	50.693	10.616	50.748	10.935	50.603	10.080	1.212
Thermal-inversion-induced fitted PM2.5 (μg/m^3)	61.543	10.114	61.242	10.337	62.027	9.724	-6.857***
Parental education expectation	4.306	1.306	4.211	1.397	4.458	1.127	-17.379***
Child education expectation	4.449	1.390	4.293	1.508	4.700	1.132	-27.515***
Household income level	2.907	0.646	2.917	0.663	2.891	0.616	3.532***
Age	14.343	1.845	13.218	1.175	16.156	1.156	-219.898***
Male (yes = 1)	0.512	0.500	0.531	0.499	0.481	0.500	8.614***
Han nationality (yes = 1)	0.981	0.135	0.980	0.138	0.983	0.130	-1.545
Hukou status (other status = 1, rural = 2, urban = 3)	2.035	0.651	1.998	0.661	2.090	0.632	-10.694***
Live in city (yes = 1)	0.663	0.473	0.652	0.477	0.681	0.466	-5.467***
Migrant (yes = 1)	0.217	0.412	0.208	0.406	0.232	0.422	-4.866***
Education level (middle school = 0, high school = 1)	0.383	0.486	0.000	0.000	1.000	0.000	n.a.
Grade (grade 7/8 = 1, grade 9 = 2, grade 10/11 = 3, grade 12 = 4)	1.999	1.173	1.131	0.338	3.399	0.490	-450.983***
Key classes (yes = 1)	0.178	0.382	0.149	0.356	0.219	0.414	-14.317***
Leader (yes = 1)	0.231	0.422	0.214	0.410	0.258	0.438	-8.912***
One-child family (yes = 1)	0.313	0.464	0.308	0.462	0.322	0.467	-2.655***
Parents' education level (below university = 0, university or above = 1)	0.115	0.319	0.112	0.315	0.120	0.325	-2.097**
Real gross domestic product per capita (thousand yuan)	11.356	5.723	11.581	5.751	10.993	5.659	9.002***
Population density (per km^2)	636.731	177.752	631.314	181.614	645.465	170.988	-7.036***
Ground-level temperature (°C)	15.059	1.053	15.002	1.082	15.153	0.997	-12.739***
Number of industrial firms per capita	3.367	1.155	3.426	1.158	3.273	1.144	11.560***
Thermal power plants effects	1.721	0.543	1.722	0.548	1.720	0.534	0.377
Forests effects	60.673	19.675	61.458	20.339	59.407	18.483	9.292***
Family relationship adjusted education investment	0.018	1.072	-0.057	1.084	0.138	1.041	-16.069***
Family relationship adjusted education investment intensity	0.022	1.098	-0.061	1.087	0.155	1.102	-17.140***

Memory	2.659	0.854	2.701	0.877	2.593	0.811	11.077***
School performance	2.862	0.865	2.863	0.895	2.862	0.816	0.091
Parental study abroad expectation	0.295	0.456	0.321	0.467	0.252	0.434	13.357***
Child study abroad expectation	0.285	0.451	0.297	0.457	0.265	0.441	6.232***
Physical health	2.787	0.899	2.818	0.922	2.739	0.859	7.684***
Depression	1.932	0.909	1.904	0.946	1.977	0.846	-7.016***
Self-worth	2.435	0.864	2.455	0.899	2.402	0.805	5.476***
Average PM2.5 in previous one year (μg/m^3)	57.479	14.244	57.709	14.660	57.109	13.540	3.735***
Average PM2.5 in previous two year (μg/m^3)	58.265	13.118	58.410	13.497	58.031	12.480	2.568**
Average PM2.5 in previous three year (μg/m^3)	60.578	12.970	60.619	13.352	60.511	12.329	0.739
Average PM2.5 in previous four year (μg/m^3)	63.058	12.797	62.979	13.171	63.185	12.169	-1.426
Average PM2.5 in previous five year (μg/m^3)	63.481	12.665	63.399	13.034	63.613	12.047	-1.500
Average PM2.5 in previous ten year (μg/m^3)	66.163	12.841	65.985	13.201	66.451	12.232	-3.214***
Has male child (yes = 1)	0.531	0.499	0.544	0.498	0.511	0.500	4.612***

Panel B. Gender

Variables	Full sample		Female		Male		Welch's t-statistic
	Mean	SD	Mean	SD	Mean	SD	
Education investment (yes = 1)	0.583	0.493	0.600	0.490	0.566	0.496	6.113***
Adjusted education investment	0.011	1.048	0.054	1.041	-0.031	1.052	7.261***
PM2.5 (μg/m^3)	50.693	10.616	50.527	10.577	50.850	10.651	-2.724***
Thermal-inversion-induced fitted PM2.5 (μg/m^3)	61.543	10.114	61.396	10.143	61.683	10.085	-2.546**
Parental education expectation	4.306	1.306	4.370	1.214	4.244	1.385	8.671***
Child education expectation	4.449	1.390	4.541	1.271	4.362	1.490	11.609***
Household income level	2.907	0.646	2.914	0.596	2.900	0.690	1.881*
Age	14.343	1.845	14.393	1.853	14.295	1.835	4.761***
Male (yes = 1)	0.512	0.500	0.000	0.000	1.000	0.000	n.a.
Han nationality (yes = 1)	0.981	0.135	0.982	0.133	0.981	0.137	0.815
Hukou status (other status = 1, rural = 2, urban = 3)	2.035	0.651	2.030	0.649	2.039	0.653	-1.055
Live in city (yes = 1)	0.663	0.473	0.653	0.476	0.673	0.469	-3.806***
Migrant (yes = 1)	0.217	0.412	0.193	0.395	0.240	0.427	-10.244***
Education level (middle school = 0, high school = 1)	0.383	0.486	0.407	0.491	0.360	0.480	8.611***
Grade (grade 7/8 = 1, grade 9 = 2, grade 10/11 = 3, grade 12 = 4)	1.999	1.173	2.047	1.187	1.954	1.158	7.113***
Key classes (yes = 1)	0.178	0.382	0.177	0.381	0.178	0.383	-0.380
Leader (yes = 1)	0.231	0.422	0.243	0.429	0.220	0.414	4.925***
One-child family (yes = 1)	0.313	0.464	0.240	0.427	0.383	0.486	-27.941***
Parents' education level (below university = 0, university or above = 1)	0.115	0.319	0.109	0.311	0.121	0.326	-3.397***
Real gross domestic product per capita (thousand yuan)	11.356	5.723	11.501	5.774	11.218	5.671	4.434***
Population density (per km^2)	636.731	177.752	632.940	179.851	640.345	175.656	-3.729***
Ground-level temperature (°C)	15.059	1.053	15.041	1.049	15.077	1.057	-3.042***
Number of industrial firms per capita	3.367	1.155	3.386	1.160	3.349	1.150	2.890***
Thermal power plants effects	1.721	0.543	1.724	0.543	1.718	0.542	0.944
Forests effects	60.673	19.675	60.720	19.704	60.627	19.647	0.422
Family relationship adjusted education investment	0.018	1.072	0.068	1.058	-0.030	1.083	8.215***
Family relationship adjusted education investment intensity	0.022	1.098	0.082	1.051	-0.036	1.138	9.716***
Memory	2.659	0.854	2.582	0.821	2.732	0.878	-15.557***

School performance	2.862	0.865	2.874	0.830	2.851	0.898	2.417**
Parental study abroad expectation	0.295	0.456	0.264	0.441	0.324	0.468	-11.765***
Child study abroad expectation	0.285	0.451	0.275	0.446	0.294	0.456	-3.825***
Physical health	2.787	0.899	2.701	0.873	2.870	0.916	-16.716***
Depression	1.932	0.909	1.913	0.873	1.950	0.942	-3.637***
Self-worth	2.435	0.864	2.411	0.831	2.457	0.894	-4.775***
Average PM2.5 in previous one year (μg/m^3)	57.479	14.244	57.283	14.172	57.666	14.311	-2.403**
Average PM2.5 in previous two year (μg/m^3)	58.265	13.118	58.080	13.065	58.442	13.166	-2.471**
Average PM2.5 in previous three year (μg/m^3)	60.578	12.970	60.375	12.924	60.772	13.011	-2.741***
Average PM2.5 in previous four year (μg/m^3)	63.058	12.797	62.841	12.765	63.264	12.824	-2.958***
Average PM2.5 in previous five year (μg/m^3)	63.481	12.665	63.265	12.637	63.686	12.690	-2.977***
Average PM2.5 in previous ten year (μg/m^3)	66.163	12.841	65.931	12.824	66.385	12.853	-3.168***
Has male child (yes = 1)	0.531	0.499	0.642	0.479	0.402	0.490	36.359***

Notes: SD = standard deviation. We assume that our unpaired data do not have equal variances, and we present Welch's *t*-statistic (middle school−high school) and (female−male).

TABLE 2
The Impact of Air Pollution on Education Investment

Dependent variable	(1) Education investment		(2) Adjusted education investment		(3) Education investment		(4) Adjusted education investment	
PM2.5 (μg/m^3)	-0.008*	(0.004)	-0.035*	(0.016)	-0.009*	(0.005)	-0.042**	(0.019)
Age	-0.006	(0.054)	0.089	(0.125)	-0.005	(0.051)	0.089	(0.118)
Age squared	0.000	(0.002)	-0.004	(0.004)	0.000	(0.002)	-0.004	(0.004)
Male (yes = 1)	-0.031***	(0.008)	-0.086***	(0.017)	-0.031***	(0.008)	-0.086***	(0.016)
Han nationality (yes = 1)	0.010	(0.026)	0.074	(0.071)	0.010	(0.025)	0.074	(0.068)
Hukou status (other status = 1, rural = 2, urban = 3)	0.019**	(0.008)	0.110***	(0.011)	0.019***	(0.007)	0.111***	(0.011)
Live in city (yes = 1)	0.102***	(0.013)	0.304***	(0.020)	0.102***	(0.012)	0.304***	(0.020)
Migrant (yes = 1)	0.012	(0.018)	0.029	(0.035)	0.012	(0.017)	0.029	(0.033)
Education level (middle school = 0, high school = 1)	0.213***	(0.021)	0.302***	(0.073)	0.213***	(0.020)	0.302***	(0.069)
Key classes (yes = 1)	-0.013	(0.023)	0.004	(0.036)	-0.013	(0.022)	0.004	(0.034)
Leader (yes = 1)	0.030	(0.031)	0.062	(0.038)	0.030	(0.029)	0.062*	(0.036)
One-child family (yes = 1)	-0.026	(0.023)	0.078**	(0.033)	-0.026	(0.021)	0.076**	(0.032)
Parents' education level (below university = 0, university or above = 1)	0.011	(0.007)	-0.008	(0.018)	0.011*	(0.007)	-0.008	(0.017)
Real gross domestic product per capita (thousand yuan)	0.053**	(0.018)	0.387***	(0.032)	0.053***	(0.017)	0.387***	(0.031)
Population density (per km^2)	-0.000	(0.005)	-0.009	(0.017)	0.000	(0.005)	-0.008	(0.017)
Ground-level temperature (°C)	0.000*	(0.000)	0.001	(0.001)	0.000**	(0.000)	0.001**	(0.001)
Number of industrial firms per capita	-0.220	(0.135)	-0.364	(0.459)	-0.243*	(0.138)	-0.508	(0.475)
Thermal power plants effects	-0.001	(0.027)	-0.044	(0.082)	0.002	(0.027)	-0.025	(0.085)
Forests effects	0.429*	(0.219)	0.724	(0.755)	0.466**	(0.225)	0.963	(0.785)
Constants	4.686*	(2.398)	7.047	(8.405)	5.122**	(2.594)	9.840	(8.981)
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	19333		19333		19333		19333	
Clusters	10		10		10		10	

Methodology	OLS	OLS	2SLS	2SLS
t-statistic (instrument)	n.a.	n.a.	5.21	5.21
F-statistic (instrument)	n.a.	n.a.	27.172	27.172

Notes: Robust standard errors are clustered by city and reported in parentheses.

* $p < .10$

** $p < .05$

*** $p < .01$

TABLE 3
The Impact of Air Pollution on Education Investment: Mediation Analysis

Panel A. Education investment

	(1)		(2)		(3)	
Direct effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.009*	(0.005)	-0.009*	(0.005)	-0.009*	(0.005)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		27.172		27.172	
Mediating effects: dependent variable =	**Parental education expectation**		**Child education expectation**		**Household income level**	
PM2.5 (μg/m^3)	-0.040**	(0.019)	-0.046***	(0.011)	-0.016*	(0.009)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		27.172		27.172	
Mediating effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.008	(0.006)	-0.008	(0.005)	-0.008*	(0.005)
Parental education expectation	0.024***	(0.006)				
Child education expectation			0.024***	(0.006)		
Household income level					0.077***	(0.007)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.181		27.157		27.161	
Control variables	YES		YES		YES	
City fixed effects	YES		YES		YES	
Year fixed effects	YES		YES		YES	
Methodology	2SLS		2SLS		2SLS	

Panel B. Adjusted education investment

	(1)		(2)		(3)	
Direct effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.042**	(0.019)	-0.042**	(0.019)	-0.042**	(0.019)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		27.172		27.172	
Mediating effects: dependent variable =	**Parent expectation**		**Child expectation**		**Household income level**	
PM2.5 (μg/m^3)	-0.040**	(0.019)	-0.046***	(0.011)	-0.016*	(0.009)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		27.172		27.172	
Mediating effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.037*	(0.020)	-0.036**	(0.018)	-0.038**	(0.017)
Parent expectation	0.128***	(0.011)				
Child expectation			0.131***	(0.012)		
Household income level					0.241***	(0.012)
Observations	19333		19333		19333	
Clusters	10		10		10	
t-statistic (instrument)	5.21		5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.181		27.157		27.161	
Control variables	YES		YES		YES	
City fixed effects	YES		YES		YES	
Year fixed effects	YES		YES		YES	
Methodology	2SLS		2SLS		2SLS	

Notes: Robust standard errors are clustered by city and reported in parentheses.

$*$ $p < .10$

** p <.05
*** p <.01

TABLE 4
The Impact of Air Pollution on Education Investment: Moderation Analysis

Dependent variable	**(1) Education investment**		**(2) Education investment**		**(3) Adjusted education investment**		**(4)Adjusted education investment**	
PM2.5 (μg/m^3)	-0.009*	(0.005)	-0.009*	(0.005)	-0.042**	(0.018)	-0.042**	(0.019)
PM2.5 (μg/m^3) * Education level	0.003	(0.002)			0.007*	(0.004)		
PM2.5 (μg/m^3) * Gender			0.000	(0.001)			0.001	(0.002)
Control variables	YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	19333		19333		19333		19333	
Clusters	10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS	
t-statistic of independent variable (instrument)	-1.33		0.02		-1.33		0.02	
t-statistic of interaction (instrument)	9.14		9.47		9.14		9.47	
Shea's partial R squared of independent variable (instrument)	0.490		0.490		0.490		0.490	
Shea's partial R squared of interaction (instrument)	0.796		0.809		0.796		0.809	

Notes: Robust standard errors are clustered by city and reported in parentheses.

* $p < .10$

** $p < .05$

*** $p < .01$

TABLE A1
Robustness Checks: Alternative Measure of Education Investment

Dependent variable	(1) Family relationship adjusted education investment		(2) Family relationship adjusted education investment intensity	
PM2.5 (μg/m^3)	-0.049***	(0.016)	-0.038***	(0.014)
Control variables	YES		YES	
City fixed effects	YES		YES	
Year fixed effects	YES		YES	
Observations	19333		19333	
Clusters	10		10	
Methodology	2SLS		2SLS	
t-statistic (instrument)	5.21		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		27.172	

Notes: Robust standard errors are clustered by city and reported in parentheses.
* $p < .10$
** $p < .05$
*** $p < .01$

TABLE A2
Robustness Checks: Cumulative Effects of Air Pollution

Panel A. Excluding air pollution in current year

Dependent variable	**(1) Education investment**		**(2) Education investment**		**(3) Education investment**		**(4) Education investment**		**(5) Education investment**		**(6) Education investment**	
Average PM2.5 in previous years (μg/m^3)	-0.006***	(0.002)	-0.008*	(0.004)	-0.012	(0.007)	-0.005	(0.015)	-0.010	(0.011)	-0.010	(0.011)
Control variables	YES		YES		YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES		YES		YES	
Observations												
Clusters	10		10		10		10		10		10	
Methodology	OLS		OLS		OLS		OLS		OLS		OLS	
Sample	1 year		2 years		3 years		4 years		5 years		10 years	

Dependent variable	(7) Adjusted education investment	(8) Adjusted education investment	(9) Adjusted education investment	(10) Adjusted education investment	(11) Adjusted education investment	(12) Adjusted education investment
Average PM2.5 in previous years (μg/m^3)	-0.026*** (0.006)	-0.035** (0.014)	-0.047* (0.024)	-0.021 (0.057)	-0.040 (0.039)	-0.043 (0.040)
Control variables	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES	YES
Observations						
Clusters	10	10	10	10	10	10
Methodology	OLS	OLS	OLS	OLS	OLS	OLS
Sample	1 year	2 years	3 years	4 years	5 years	10 years

Panel B. Including air pollution in current year

Dependent variable	(1) Education investment		(2) Education investment		(3) Education investment		(4) Education investment		(5) Education investment		(6) Education investment	
PM2.5 ($\mu g/m^3$)	0.205	(8.349)	-0.023	(0.051)	-0.012	(0.018)	-0.017*	(0.009)	-0.014	(0.012)	-0.017	(0.014)
Average PM2.5 in previous years ($\mu g/m^3$)	-0.142	(5.540)	0.016	(0.055)	0.006	(0.026)	0.025	(0.020)	0.012	(0.020)	0.018	(0.025)
t-statistic (instrument)	0.02		0.45		0.87		1.56		1.37		0.95	
Kleibergen-Paap rk Wald F-statistic (instrument)	0.001		0.201		0.761		2.444		1.891		0.903	
Control variables	YES		YES		YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES		YES		YES	
Observations												
Clusters	10		10		10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS		2SLS		2SLS	
Sample	1 year		2 years		3 years		4 years		5 years		10 years	

Dependent variable	(7) Adjusted education investment		(8) Adjusted education investment		(9) Adjusted education investment		(10) Adjusted education investment		(11) Adjusted education investment		(12) Adjusted education investment	
PM2.5 (μg/m^3)	-0.791	(30.697)	-0.154	(0.284)	-0.080	(0.078)	-0.081**	(0.041)	-0.073	(0.049)	-0.092	(0.068)
Average PM2.5 in previous years (μg/m^3)	0.498	(20.358)	0.133	(0.310)	0.067	(0.107)	0.122	(0.084)	0.079	(0.081)	0.108	(0.117)
t-statistic (instrument)	0.02		0.45		0.87		1.56		1.37		0.95	
Kleibergen-Paap rk Wald F-statistic (instrument)	0.001		0.201		0.761		2.444		1.891		0.903	
Control variables	YES		YES		YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES		YES		YES	
Observations												
Clusters	10		10		10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS		2SLS		2SLS	
Sample	1 year		2 years		3 years		4 years		5 years		10 years	

Notes: Robust standard errors are clustered by city and reported in parentheses.

* p <.10
** p <.05
*** p <.01

TABLE A3
Robustness Checks: Non-linear Effects of Air Pollution

	(1)		(2)	
Dependent variable	**Education investment**		**Adjusted education investment**	
PM2.5 (μg/m^3)	-0.095**	(0.041)	-0.298**	(0.133)
PM2.5 squared (μg/m^3)	0.001**	(0.000)	0.002*	(0.001)
Control variables	YES		YES	
City fixed effects	YES		YES	
Year fixed effects	YES		YES	
Observations	19333		19333	
Clusters	10		10	
Methodology	2SLS		2SLS	
t-statistic of independent variable (instrument)	1.49		1.49	
t-statistic of squared term (instrument)	-0.99		-0.99	
Shea's partial R squared of independent variable (instrument)	0.623		0.623	
Shea's partial R squared of squared term (instrument)	0.673		0.673	

Notes: Robust standard errors are clustered by city and reported in parentheses.
∗ *p* <.10
∗∗ *p* <.05
∗∗∗ *p* <.01

TABLE A4
Robustness Checks: Potential Mediators

Panel A. Education investment

	(1)		(2)		(3)	
Direct effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.002	(0.003)	-0.002	(0.003)	-0.0090*	(0.005)
Observations	19222		19222		19333	
Clusters	10		10		10	
t-statistic (instrument)	4.97		4.97		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.718		24.718		27.172	
Mediating effects: dependent variable =	**Memory**		**School performance**		**Parental study abroad expectation**	
PM2.5 (μg/m^3)	-0.036***	(0.004)	-0.050***	(0.013)	-0.013**	(0.006)
Observations	19222		19222		19333	
Clusters	10		10		10	
t-statistic (instrument)	4.97		4.97		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.718		24.718		27.172	
Mediating effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.002	(0.003)	-0.001	(0.003)	-0.0087*	(0.005)
Memory	0.009	(0.008)				
School performance			0.020***	(0.007)		
Parental study abroad expectation					0.027***	(0.011)
Observations	19222		19222		19333	
Clusters	10		10		10	
t-statistic (instrument)	4.97		4.97		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.714		24.733		27.195	

Control variables	YES	YES	YES
City fixed effects	YES	YES	YES
Year fixed effects	YES	YES	YES
Methodology	2SLS	2SLS	2SLS

	(4)		(5)		(6)		(7)	
Direct effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.0090*	(0.005)	-0.002	(0.003)	-0.002	(0.003)	-0.002	(0.003)
Observations	19333		19222		19222		19222	
Clusters	10		10		10		10	
t-statistic (instrument)	5.21		4.97		4.97		4.97	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		24.718		24.718		24.718	
Mediating effects: dependent variable =	**Child study abroad expectation**		**Physical health**		**Depression**		**Self-worth**	
PM2.5 (μg/m^3)	-0.010***	(0.003)	-0.047***	(0.015)	-0.017	(0.019)	-0.045***	(0.010)
Observations	19333		19222		19222		19222	
Clusters	10		10		10		10	
t-statistic (instrument)	5.21		4.97		4.97		4.97	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		24.718		24.718		24.718	
Mediating effects: dependent variable =	**Education investment**		**Education investment**		**Education investment**		**Education investment**	
PM2.5 (μg/m^3)	-0.0087*	(0.005)	-0.002	(0.003)	-0.002	(0.003)	-0.001	(0.003)
Child study abroad expectation	0.034***	(0.011)						
Physical health			0.015**	(0.007)				
Depression					0.011	(0.007)		
Self-worth							0.022***	(0.005)
Observations	19333		19222		19222		19222	
Clusters	10		10		10		10	

t-statistic (instrument)	5.21	4.97	4.97	4.97
Kleibergen-Paap rk Wald F-statistic (instrument)	27.178	24.710	24.687	24.709
Control variables	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Methodology	2SLS	2SLS	2SLS	2SLS

Panel B. Adjusted education investment

	(1)		(2)		(3)	
Direct effects: dependent variable =	**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**	
PM2.5 (μg/m^3)	-0.029**	(0.014)	-0.029**	(0.014)	-0.042**	(0.019)
Observations	19222		19222		19333	
Clusters	10		10		10	
t-statistic (instrument)	4.97		4.97		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.718		24.718		27.172	
Mediating effects: dependent variable =	**Memory**		**School performance**		**Parental study abroad expectation**	
PM2.5 (μg/m^3)	-0.036***	(0.004)	-0.050***	(0.013)	-0.013**	(0.006)
Observations	19222		19222		19333	
Clusters	10		10		10	
t-statistic (instrument)	4.97		4.97		5.21	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.718		24.718		27.172	
Mediating effects: dependent variable =	**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**	
PM2.5 (μg/m^3)	-0.024*	(0.014)	-0.022	(0.014)	-0.040**	(0.018)
Memory	0.147***	(0.014)				
School performance			0.158***	(0.011)		
Parental study abroad expectation					0.123***	(0.031)
Observations	19222		19222		19333	
Clusters	10		10		10	

t-statistic (instrument)	4.97	4.97	5.21
Kleibergen-Paap rk Wald F-statistic (instrument)	24.714	24.733	27.195
Control variables	YES	YES	YES
City fixed effects	YES	YES	YES
Year fixed effects	YES	YES	YES
Methodology	2SLS	2SLS	2SLS

	(4)		(5)		(6)		(7)	
Direct effects: dependent variable =	**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**	
PM2.5 (μg/m^3)	-0.042**	(0.019)	-0.029**	(0.014)	-0.029**	(0.014)	-0.029**	(0.014)
Observations	19333		19222		19222		19222	
Clusters	10		10		10		10	
t-statistic (instrument)	5.21		4.79		4.79		4.79	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		24.718		24.718		24.718	
Mediating effects: dependent variable =	**Child study abroad expectation**		**Physical health**		**Depression**		**Self-worth**	
PM2.5 (μg/m^3)	-0.010***	(0.003)	-0.047***	(0.015)	-0.017	(0.019)	-0.045***	(0.010)
Observations	19333		19222		19222		19222	
Clusters	10		10		10		10	
t-statistic (instrument)	5.21		4.79		4.79		4.79	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.172		24.718		24.718		24.718	
Mediating effects: dependent variable =	**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**		**Adjusted education investment**	
PM2.5 (μg/m^3)	-0.040**	(0.019)	-0.023*	(0.012)	-0.030**	(0.015)	-0.024*	(0.013)
Child study abroad expectation	0.145***	(0.034)						
Physical health			0.130***	(0.012)				
Depression					-0.042***	(0.011)		
Self-worth							0.127***	(0.011)
Observations	19333		19222		19222		19222	

Clusters	10	10	10	10
t-statistic (instrument)	5.21	4.79	4.79	4.79
Kleibergen-Paap rk Wald F-statistic (instrument)	27.178	24.710	24.687	24.709
Control variables	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES
Methodology	2SLS	2SLS	2SLS	2SLS

Notes: Robust standard errors are clustered by city and reported in parentheses.

∗ p <.10

∗∗ p <.05

∗∗∗ p <.01

TABLE A5
Robustness Checks: Potential Moderators

Dependent variable		(1) Education investment		(2) Education investment		(3) Adjusted education investment		(4) Adjusted education investment	
PM2.5 (μg/m^3)		-0.009*	(0.005)	-0.010	(0.012)	-0.041**	(0.018)	-0.061*	(0.033)
PM2.5 (μg/m^3) * Grade	1.grade	0.000	(.)			0.000	(.)		
	2.grade	-0.001	(0.001)			-0.003	(0.003)		
	3.grade	0.003	(0.002)			0.007**	(0.003)		
	4.grade	0.003	(0.003)			0.005	(0.005)		
PM2.5 (μg/m^3) * Male child				0.000**	(0.000)			0.000	(0.000)
Control variables		YES		YES		YES		YES	
City fixed effects		YES		YES		YES		YES	
Year fixed effects		YES		YES		YES		YES	
Observations		19333		7500		19333		7500	
Clusters		10		10		10		10	
Methodology		2SLS		2SLS		2SLS		2SLS	
t-statistic of independent variable (instrument)		0.66		1.29		0.66		1.29	
t-statistic of interaction (instrument)		0.20, 0.60, 10.31		56.19		0.20, 0.60, 10.31		56.19	
Shea's partial R squared of independent variable (instrument)		0.490		0.466		0.490		0.466	
Shea's partial R squared of interaction (instrument)		0.781, 0.790, 0.797		0.993		0.781, 0.790, 0.797		0.993	
Sample		Full sample		Female		Full sample		Female	

Notes: Robust standard errors are clustered by city and reported in parentheses. Note that for the moderation effect of male child, we use female sample.

* $p < .10$
** $p < .05$
*** $p < .01$

TABLE A6
Robustness Checks: Sub-group Analysis according to Living Areas

Dependent variable	**(1) Education investment**		**(2) Education investment**		**(3) Adjusted education investment**		**(4) Adjusted education investment**	
PM2.5 ($\mu g/m^3$)	-0.014***	(0.002)	-0.005	(0.012)	-0.058***	(0.012)	-0.008	(0.024)
Control variables	YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	14428		4905		14428		4905	
Clusters	10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS	
t-statistic (instrument)	4.47		3.76		4.47		3.76	
Kleibergen-Paap rk Wald F-statistic (instrument)	19.961		14.156		19.961		14.156	
Sample	Urban		Rural		Urban		Rural	

Notes: Robust standard errors are clustered by city and reported in parentheses.
∗ p <.10
∗∗ p <.05
∗∗∗ p <.01

TABLE A7
Robustness Checks: Sub-group Analysis according to One-child Family

Dependent variable	**(1)** **Education investment**		**(2)** **Education investment**		**(3)** **Adjusted education investment**		**(4)** **Adjusted education investment**	
PM2.5 (μg/m^3)	-0.024***	(0.006)	0.000	(0.009)	-0.057***	(0.011)	-0.027	(0.020)
Control variables	YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	5628		13705		5628		13705	
Clusters	10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS	
t-statistic (instrument)	8.47		3.99		8.47		3.99	
Kleibergen-Paap rk Wald F-statistic (instrument)	71.862		15.957		71.862		15.957	
Sample	One-child family		Non-one-child family		One-child family		Non-one-child family	

Notes: Robust standard errors are clustered by city and reported in parentheses.
∗ p <.10
∗∗ p <.05
∗∗∗ p <.01

TABLE A8
Robustness Checks: Sub-group Analysis according to Education Level

Dependent variable	**(1) Education investment**		**(2) Education investment**		**(3) Adjusted education investment**		**(4) Adjusted education investment**	
PM2.5 (μg/m^3)	-0.005	(0.004)	-0.017	(0.011)	-0.042***	(0.016)	-0.050**	(0.024)
Control variables	YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	11365		7968		11365		7968	
Clusters	10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS	
t-statistic (instrument)	5.23		4.24		5.23		4.24	
Kleibergen-Paap rk Wald F-statistic (instrument)	27.331		17.983		27.331		17.983	
Sample	Middle school		High school		Middle school		High school	

Notes: Robust standard errors are clustered by city and reported in parentheses.
∗ p <.10
∗∗ p <.05
∗∗∗ p <.01

TABLE A9
Robustness Checks: Sub-group Analysis according to Graduation Cohort

Dependent variable	**(1) Education investment**		**(2) Education investment**		**(3) Adjusted education investment**		**(4) Adjusted education investment**	
PM2.5 (μg/m^3)	-0.013***	(0.003)	0.008	(0.015)	-0.051***	(0.017)	-0.005	(0.032)
Control variables	YES		YES		YES		YES	
City fixed effects	YES		YES		YES		YES	
Year fixed effects	YES		YES		YES		YES	
Observations	14808		4525		14808		4525	
Clusters	10		10		10		10	
Methodology	2SLS		2SLS		2SLS		2SLS	
t-statistic (instrument)	4.98		5.24		4.98		5.24	
Kleibergen-Paap rk Wald F-statistic (instrument)	24.763		27.524		24.763		27.524	
Sample	Non-graduation cohort		Graduation cohort		Non-graduation cohort		Graduation cohort	

Notes: Robust standard errors are clustered by city and reported in parentheses.
∗ *p* <.10
∗∗ *p* <.05
∗∗∗ *p* <.01

TABLE A10
Robustness Checks: Oster Test

Dependent variable	**(1) Baseline effects beta**			**(2) Controlled effect beta**			**(3) Bias-adjusted beta (R_{max} = 1.3R)**
Education investment	-0.003***	(0.001)	[.]	-0.009*	(0.005)	[0.071]	-0.009
Adjusted education investment	-0.014***	(0.003)	[0.011]	-0.042**	(0.019)	[0.100]	-0.042

Notes: Robust standard errors are clustered by city and reported in parentheses. R squared is reported in square brackets.
$*$ $p<.10$
$**$ $p<.05$
$***$ $p<.01$