Prenatal exposure to pollution, subsequent parental behaviour and educational achievement

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Abstract

Prenatal exposure to air pollution has been shown to have adverse effects on health and educational achievement. The size of these effects may depend on parental involvement in the child's development. Using data from Germany, we investigate such interaction effects on entry into the academic secondary-school track (*Gymnasium*) and on school grades. To deal with potential endogeneity of pollution exposure, we leverage variations in the height of the planetary boundary layer, an exogenous atmospheric variable strongly predicting pollution levels. We find that higher in-utero pollution exposure decreases the likelihood of entering the academic track, especially among low-SES children. Importantly, high maternal involvement in engaging activities effectively mitigates the adverse effects of pollution, while a high frequency of passive, screen-based activities with the child does not moderate pollution effects.

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1 Introduction

According to the developmental origins hypothesis, conditions in utero and around birth can shape a person's subsequent health trajectory (Almond, Currie, and Duque, 2018). In particular, a growing number of studies have found effects of prenatal exposure to air pollution on later life health and socioeconomic outcomes (e.g. cognitive skills, educational achievement, income).

It is conceivable that the extent to which early-life pollution exposure affects these outcomes depends on parental investment in the child's development (and, more in general, on parental behaviour) during the first years of life. This is relevant as it opens up a scope for policy interventions. Notice that effect heterogeneity can act as a driver of socio-economic inequality and the intergenerational transmission of inequality. In particular, if high-SES parents mitigate effects of adverse early-life pollution but low-SES parents do not, then the pollution in and by itself exacerbates socio-economic inequality among the offspring.

Combining data from a German longitudinal household survey and atmospheric datasets, this paper investigates the causal effect of prenatal exposure to pollution on educational achievement, and directly assesses how parental involvement during early childhood moderates this effect. To measure educational achievement, we focus on the transition from elementary school to the academic track in secondary school (*Gymnasium*).[1] In the light of the rigid early tracking of the German education system, the secondary school track is a meaningful indicator of the performance in primary school but it is also a strong predictor of the educational trajectory of the child, being highly correlated with the enrolment and completion of tertiary education (Dustmann, 2004; Müller and Schneider, 2013).

To deal with potential endogeneity in the exposure to air pollution, e.g. due to sorting and avoidance behaviour, we leverage plausibly exogenous variation in the height of the planetary boundary layer (BLH), an atmospheric variable which strongly affects the concentration of pollutants on the ground.

Our results show that children exposed to a lower average BLH (and thus worse pollution) in utero are less likely to enroll to the academic track. This is in line with previous studies finding negative effects of prenatal pollution exposure on educational achievement and cognitive skills in developed and developing countries (Sanders, 2012; Bharadwaj et al., 2017; Molina, 2021). It turns out that parental, and especially maternal, education levels mitigate the adverse effects

[1]We also consider school grades at ages 12-14. However, to some extent, grading may have idiosyncratic school-specific and region-specific elements, and an individual grade may depend on the relative performance in the relevant cohort.

of exposure. A plausible explanation is that higher educated parents, who are also likely to have better resources and financial means, are better able to invest in the child's development. Next, we examine whether (and if so, how) maternal engagement throughout early childhood moderates the effect of pollution exposure on the transition into the academic track[2]. We find that a high frequency of engaging activities carried out with the child can strongly mitigate the adverse effects of pollution exposure. In particular, cognitively stimulating activities, like reading to the child, are the main driver of this gradient. Conversely, passive entertainment activities with the child, such as watching tv or playing video games, do not moderate the adverse effect of pollution.

Our study contributes to several strands of research. First, we contribute to the literature on the role of parental involvement in the child's human capital development. A few studies finding a socioeconomic gradient in the effect of pollution on educational achievement hint at the role of parental involvement as a possible explanatory mechanism, but do not explicitly test it (Jans, Johansson, and Nilsson, 2018; Bernardi and Keivabu, 2024). Second, we contribute to the literature on the developmental origins of health and disease. This literature typically hypothesises a biological pathway from early-life exposure to later-life outcomes. However, if parental behaviour is found to moderate effect sizes then this creates opportunities for policy interventions. Specifically, policies aimed at the type and frequency of joint activities of parents and children may help to mitigate adversities caused by in-utero environmental exposures. A small number of studies examines how parents adjust investments in response to the child's conditions at birth and in early life. In particular, these studies assess whether parents increase or decrease their investments in response to early insults to the child (i.e. compensating or reinforcing investments) and whether this depends on the socioeconomic status of the parents (Hsin, 2012; Restrepo, 2016; Fan and Porter, 2020). Zhang et al. (2024) estimate the effect of prenatal pollution exposure on cognitive test scores in China, finding worse effects for females than for males. To explain this gradient, they show that parents tend to be more involved with their male child (i.e. they help more with his homework) when exposed to higher pollution in-utero. Differently from their study, we do not find that parents adjust their activities in response to pollution exposure. Therefore, in our setting of an affluent Western society, parental activities act as moderators only. Moreover, the activities we examine are carried out in early childhood and before the start of formal education. Third, our identification strategy is related to the recent

[2]Throughout the paper, for expositional reasons, we often refer to high (low) pollution exposure to denote low (high) BLH.

literature using atmospheric mechanisms or conditions, such as thermal inversion or boundary layer height, as exogenous drivers of pollution. The use of these atmospheric mechanisms has several advantages over other identification strategies. First, the theoretical effect on air pollution is clear and widely acknowledged. Second, differently from within-family studies, this strategy relies on cross-family comparisons, thus using larger and more representative samples. Third, these atmospheric phenomena are always present and vary over time, so this strategy does not require narrow time-windows around a cutoff for identification, and allows longer time periods for the analysis. Many studies use thermal inversions to identify exogenous changes in pollution levels (Arceo, Hanna, and Oliva, 2016; Jans, Johansson, and Nilsson, 2018; Molina, 2021; Colmer et al., 2021; Thies, 2024). While thermal inversion is usually operationalized as a binary variable (whether it occurs or not), regardless of its intensity, BLH is actually a continuous variable, and as such it may capture the strength of the phenomenon, allowing for a more flexible specification. Moreover, BLH measures are becoming increasingly available through atmospheric reanalysis models (Schwartz, Bind, and Koutrakis, 2017; Godzinski and Castillo, 2021).

The outline of our paper is as follows: Section 2 provides background on the effects of fetal exposure to air pollution on educational achievement and gives an overview of the different identification strategies used in the related literature; Section 3 describes the data; Section 4 illustrates the empirical strategy; Section 5 gives the main results, including robustness checks; and Section 6 concludes.

2 Background

2.1 Air pollution and educational achievement

A substantial amount of medical and epidemiological evidence documents how pollutants may damage fetal development. The main harmful pollutants are particulate matter (PM2.5 and PM10) and carbon monoxide (CO). Particulate matter can circulate in fetal blood, inducing oxidative stress and inflammations in the fetus and increasing the risk of hampered brain development and cognitive disorders after birth (Guxens et al., 2018; Chen et al., 2021). Carbon monoxide binds to hemoglobin and limits the body's ability to deliver oxygen to vital organs and tissues (Gorman et al., 2003; Smithline et al., 2003); this can affect the fetus indirectly, as the mother transmits less oxygen, and directly, as CO crosses the placental barrier to circulate in fetal blood and gain access to the developing brain, with long-term consequences on neurocognitive functions (R. J. Levy, 2015). For brain development, gestation is particularly critical, because brain formation then proceeds rapidly and the damage to the nervous system due to exposure in this period can be irreversible (Prado Bert et al., 2018).

Drawing from these premises, an expanding literature has examined effects of prenatal exposure to air pollution on human capital and socioeconomic outcomes. These include earnings and labour market performance (Isen, Rossin-Slater, and Walker, 2017; Black et al., 2019), educational achievement (Bharadwaj et al., 2017; Marcotte, 2017), crime (Grönqvist, Nilsson, and Robling, 2020), and measures of cognitive skills, such as fluid intelligence (Molina, 2021) as well as measures of non-cognitive skills. Notably, Thies (2024) examines the effect of prenatal pollution exposure on noncognitive skills during childhood, using SOEP data. Thies (2024) instruments air pollution levels with thermal inversions and finds that higher exposure in utero increases neuroticism and negatively affects emotional stability at ages 5-10.

A few studies have assessed the presence of a socioeconomic gradient in the effect of prenatal pollution exposure on the outcomes mentioned above, finding low socioeconomic status (SES) children to be the most negatively affected group (Jans, Johansson, and Nilsson, 2018; Thies, 2024). This suggests that the effect of prenatal exposure to air pollution on these outcomes is not only the result of biological channels (i.e. the direct effect on health, cognitive and non-cognitive skills) but also depends on parental involvement during the child's early development.

2.2 Atmospheric drivers of pollution

The main challenge for the identification of effects of air pollution exposure on human capital and socioeconomic outcomes is that exposure is not random across locations and households. First, households from a higher socioeconomic status could have higher preferences for clean air, or more monetary means to realize clean air exposure, thus taking the level of pollution of an area into account when deciding where to live. Supporting this scenario, several studies show that air quality is reflected in house prices (Chay and Greenstone, 2005; Sullivan, 2016). Residential sorting with respect to air quality may bias the estimates of the effect of pollution on educational achievement if high SES parents are more likely to invest in their children's schooling and development. Moreover, at any given location, the actually experienced atmospheric air pollution, and its consequent effect on fetal development, depend on the awareness and behavioural responses of the parents. These could consist in defensive investments, for example in pharmaceutical products (Deschenes, Greenstone, and Shapiro, 2017), or in avoidance behaviours, by reducing the time spent outdoors in response to smog alerts (Neidell, 2009; Moretti and Neidell, 2011).

To deal with these selectivity concerns, past studies have employed a variety of empirical strategies. A number of studies have relied on within-family analyses with mother fixed effects, focusing on within-location temporal variations (e.g. Currie, Neidell, and Schmieder, 2009; Coneus and Spiess, 2012; Bharadwaj et al., 2017). Using Chilean data, Bharadwaj et al. (2017), find strong negative effects of fetal exposure to carbon monoxide and particulate matter on fourth-grade test scores. Other studies have leveraged nation-wide policies tackling air pollution (Chay and Greenstone, 2003a; Isen, Rossin-Slater, and Walker, 2017), or the more recent introductions of Low Emission Zones at the local level (Brehm et al., 2025; Conte Keivabu and Rüttenauer, 2022). In a similar way, economic shocks have been considered as exogenous sources of variation in pollution levels for limited periods of time. For example, the reduction in prenatal exposure to air pollution during the US industrial recession of the early 1980s has been shown to have beneficial effects, reducing infant mortality (Chay and Greenstone, 2003b) and increasing high school test scores (Sanders, 2012).

Recently, with the increasing availability of atmospheric data, a number of studies have used atmospheric events and characteristics, notably thermal inversion and planetary boundary layer height, as exogenous shifters of air pollution (as referenced in Section 1). The use of these measures comes from the atmospheric sciences literature which shows that these phenomena are important determinants of the dispersion and the concentration of pollutants on the ground (Jacobson, 2002; Levi et al., 2020).

The planetary boundary layer (PBL) is the lowest part of the troposphere, in direct contact with the earth's surface. This layer is characterized by strong vertical mixing, as the surface friction and the vertical temperature differences give rise to turbulent movements of air, pollutants and moisture within it (Seinfeld and Pandis, 2016). The rapid vertical mixing prevents the transport of pollutants from the boundary layer to the nonturbulent free atmosphere above, thus constraining the dispersion of pollutants within the PBL (Schwartz, Bind, and Koutrakis, 2017). Therefore, as the height of the boundary layer (BLH) increases (decreases), the air volume available for dispersion increases (decreases) and the concentration of pollutants on the surface decreases (increases). In addition to varying strongly during the day, BLH exhibits a strong seasonal variability: Figure A1 shows in our data the strong negative correlation between

BLH and PM2.5 across months in our data. Thermal inversions are closely related to boundary layer height: during a thermal inversion, the temperature, which usually decreases with height, sharply increases at the top of the boundary layer (Godzinski and Castillo, 2021). Being determined by vertical air layers, these atmospheric phenomena are plausibly not related to human activities and business cycles, but are purely meteorological in nature, and thus are plausibly exogenous drivers of variation in air pollution.

3 Data

3.1 Socioeconomic data

Socioeconomic data are from the German Socio-Economic Panel Study (SOEP, Goebel et al., 2019), a large longitudinal household survey, starting in 1984, covering approximately 30000 people from 20000 households every year. It contains detailed socioeconomic and demographic information at the household and individual level and closely follows parents and children over time.

Outcome variables Our main outcomes of interest are measures of educational attainment in late childhood and early adolescence, notably whether the student enrols in the academic track in secondary school, *Gymnasium*. German education is characterized by a rigorous early tracking system, where, based on the performance in the final years of primary school, students are assigned to one of the following secondary school tracks (generally starting at age ten): the lower track, *Hauptschule*, lasting five years, the medium track, *Realschule*, lasting six years and the higher or academic track, *Gymnasium*, which lasts eight or nine years. Lower and medium tracks generally prepare students for apprenticeships and vocational trainings in blue-collar or white-collar occupations, whereas *Gymnasium* offers a more academic program and is the only track granting access to university[3]. Next to the classical three-tiered system, several states also have comprehensive schools (*Gesamtschule*), that offer multiple educational tracks in the same institute. Depending on the educational path chosen within the school, students can therefore obtain equivalent qualifications to those that are obtained in the lower, medium and higher

[3]Students start secondary school in the fifth grade, at age 10 in all federal states except for Berlin and Brandenburg, where secondary school starts in the seventh grade, at age 12.

tracks[4].

Students are allocated to one of the secondary school tracks based on the primary school teacher's recommendation, which takes into account the children's performance in the last years of primary school. While this recommendation is not binding in most states, parents tend to follow it[5]. While in principle students can change track during the course of secondary school, mobility across tracks, and especially upward mobility, is rare (Dustmann, Patrick A Puhani, and Schönberg, 2017). Therefore, the rate of transition to *Gymnasium* is a meaningful indicator of early educational performance. It has major implications for later-life socioeconomic outcomes, such as career trajectories and earnings (Dustmann, 2004). This outcome has been studied in relation to the effects of pollution exposure. The recent study by Brehm et al. (2025) shows that the progressive implementation of Low Emission Zones in Germany significantly increased the rate of transition to the academic track for primary school children.

As outcome measures we also consider school grades in German and Maths at ages twelve and fourteen. Concerning the latter, note that the grading system from primary school through high school uses a six-point scale, ranging from 1 (excellent) to 6 (insufficient). For ease of interpretation, we reverse this scale. While school grades are available during primary school (at ages eight and ten) as well, these are not strongly indicative of school performance and display low variation, with values ranging from 1 to 3.

Maternal activities We collect information on parental activities carried out with the child throughout childhood: the *Mother and child* questionnaires ask the mother in multiple waves how frequently she has carried out a series of activities with the child over the past couple of weeks prior to the survey, with values ranging from 'Every day' to 'Never'[6]. In this study, we focus on activities carried out at ages one, three, and six, that is, before the beginning of formal education; by doing this, we are not considering activities that parents may carry out in response to early school outcomes, which in turn are correlated with our outcomes of interest.

From the list of parental activities, we do not consider outdoor activities (e.g. going to the playground, taking walks) and activities with a high number of missing observations (e.g.

[4]Depending on regional and organizational variations, *Gesamtschule* is referred to by a vast array of different terms, including *Mittelschule*, *Regelschule* and *Sekundarschule* (for schools that combine the lower and medium track) and *Integrierte Gesamtschule*, *Oberschule*, *Stadtteilschule* and *Gemeinschaftschule* (for schools that combine all three tracks).

[5]Teacher's recommendation was binding for the whole period of interest (from 2010 onwards) in Bavaria, Brandenburg, Saxony and Thuringia. Source: `www.kmk.org`

[6]Specifically, mothers indicate the frequency of the activities in a 4-point scale: 'Daily', 'Several times a week', 'At least once a week', 'Not at all'.

reading picture books). We are left with the following activities recorded at ages one, three and six:

- Singing songs to or with the child
- Painting or doing arts and crafts
- Reading or telling stories
- Watching television or videos with the child

For children aged six, we also have:

- Playing cards, board games or other games together
- Playing computer or internet games together
- Going to children's theater productions, circus, museums, exhibitions, etc.

To make the values of parental activities comparable across ages, for each activity we standardize the values within each age and then take the average of the standardized values across ages. Then, to measure maternal activities across early childhood, we follow a twofold approach. On the one hand, we consider separately the four activities recorded at ages one, three and six to better understand the role of each activity. We define for each activity a dummy for high relative frequency, which takes value 1 when the average of the age-standardized value is above the mean.

On the other hand, we combine information from these activities by means of a principal component analysis, following the approach of Del Bono et al. (2016), and we find evidence of two common factors[7]. Table A1 in the Appendix shows the factor loadings of each activity. We see that most activities load predominantly on the first factor, while watching tv and playing computer games load almost exclusively on the second factor[8]. We can interpret the first factor as a measure of paretal involvement in active and engaging activities, E_a, and the second as a measure of parental involvement in passively entertaining activities, P_a. We then define a dummy for each factor in the same way as above. These dummies can be interpreted

[7]These are obtained by selecting factors with eigenvalue greater than or equal to 1 and by applying an oblique rotation to allow for correlation between factors. The two factors jointly explain 50% of the total variance at all ages combined, with a correlation coefficient of 0.11.

[8]Cultural trips loads modestly on both factors and has high uniqueness (0.88). This indicates that its variance isn't well captured by either factor, suggesting it might represent a somewhat distinct type of activity or be influenced by factors not extracted here.

respectively as high relative frequency of engaging activities and high relative frequency of passively entertaining activities.

Location The county (or *Kreis*) is the unit of location at our disposal in the data[9]. The county of residence at birth and the date of birth are used to assign pollution exposure to individuals. In fact, information on the county of residence at birth is available for around 60% of the sample. For the remaining cases, where the households entered the survey after the child was born, we proxy the county of birth with the county of residence in the year in which the household entered the survey. For German-born children up to age 18, internal (cross-county) migration rates have been shown to be low in the period of interest (Sander, 2017; Stawarz and Sander, 2019). Admittedly, the measurement error may lead to attenuation bias, in which case our estimates represent a lower bound of the effect.

From the household and individual questionnaires, we also collect information on a wide range of demographic and socioeconomic characteristics. For the analysis sample, we consider only children from two-parent or single-parent households with nonmissing information on parental education, thus excluding children with unknown family education background. We focus on children born between 2000 and 2010, who enrolled in secondary school at age ten or higher between 2010 and 2021, the last year available in SOEP. This results in N=5902 children for the *Gymnasium* sample and N=3286 or N=3285 for the German grade sample and the Maths grade sample, respectively. This reduction in sample size is due to the fact that the school grades sample includes students who are aged twelve or fourteen at the time of the survey: given that data on secondary school grades in SOEP are available from 2014 and we follow children until 2021, the school grades sample includes children born between 2002 and 2009. Descriptive statistics are reported in Table 1.

3.2 Atmospheric and air pollution data

The atmospheric data is collected from the ERA5 reanalysis dataset available in the Climate Data Store of the European Centre for Medium-Range Weather Forecasts (ECMWF), for the period 1999-2010. The data is available at an hourly level on a 0.25° latitude x 0.25° longitude

[9]Counties are the primary subdivision higher than a municipality in Germany and correspond to NUTS 3 administrative units. As of now, Germany is divided in 400 counties; 294 of these are rural (*Landkreis* or *Kreis*) and 106 are urban (*kreisfreie Städte* or *Stadtkreise*): these are usually large cities that do not belong to counties but take on county responsibilities themselves.

Table 1: Descriptive statistics

	Mean	Std.Dev.	N
Gymnasium	0.43	0.495	5902
German	4.33	0.85	3247
Maths	4.27	0.99	3246
BLH (m)	574.66	62.08	5902
PM2.5 ($\mu g/m^3$)	14.88	2.13	5902
Mother's Age at Birth	30.3	5.53	5902
Birth Order	1.93	1.09	5902
Migration Background	0.29	0.45	5902
Female	0.49	0.5	5902
Single Parent HH	0.19	0.39	5883
Mother: No High School	0.15	0.36	5885
Mother: High School	0.58	0.49	5885
Mother: University	0.27	0.44	5885
Father: No High School	0.11	0.32	4786
Father: High School	0.5	0.5	4786
Father: University	0.39	0.49	4786

Descriptive statistics for the sample of children for whom there is information on secondary school track (the *Gymnasium* sample). German and Maths are reported for the school grades sample.

grid, which roughly equals a 28 km x 17.5 km grid in Germany. To assign the value of boundary layer height to a county, we average the hourly values over the month and then compute the simple mean of the grids within the county's borders. As illustrated in Table 1, the average height of planetary boundary layer during gestation for the sample is around 575 meters with a standard deviation of 62 meters.

The same data source provides observations of weather conditions at the monthly level at the $0.1°$ latitude x $0.1°$ longitude grid, namely total precipitation, surface temperature, and eastward and northward components of the 10-metre wind to compute wind speed. The monthly averages are assigned to the county in the same way as described for boundary layer height.

In terms of actual pollution exposure, it would be attractive to have granular spatial and temporal observations of surface concentrations of all the main pollutants known to affect fetal development, namely PM2.5, PM10 and CO. For PM2.5, we collect data on monthly average concentrations, available at a $0.1°$ latitude x $0.1°$ longitude grid from the Atmospheric Composition Analysis Group (ACAG). Estimates of PM2.5 concentration at this granular level are obtained through a model that combines satellite-derived estimates with chemical transport models, and calibrates the ground-based observations using deep learning (Shen et al., 2024).

For PM10 ad CO, the only data available come from the German federal environmental agency (Umweltbundesamt), which provides daily values of concentrations measured at outdoor monitoring stations. Figures A2 and A3 show the distribution of active stations in 2000 and 2010 in Germany for PM10 and CO, respectively. As we can see, monitoring stations were not distributed homogeneously across the territory and many of them were not continuously active during the period of interest: most of PM10 outdoor stations were not active during the early 2000s, since strict air quality standards had not yet been established by the European Union, while for CO we observe the opposite trend, with active stations sharply decreasing over time[10].

4 Empirical strategy

4.1 Boundary layer height and air pollution

As previously mentioned in section 2.2, boundary layer height is an important atmospheric determinant of pollution levels on the ground. Changes in BLH result from the combination of seasonal fluctuations, atmospheric conditions (such as wind, temperature and precipitations) and geographic characteristics. In line with the previous literature (e.g. Arceo, Hanna, and Oliva, 2016; Molina, 2021), we argue that after controlling for all the relevant atmospheric conditions and for geographic and temporal patterns, residual variations in BLH are as good as random and thus generate exogenous variations in air pollution. In our setting, the causal effect of BLH on air pollution P in county c during the nine-month period ending in month m in year y can be retrieved by the following equation:

$$P_{cym} = \beta_1 BLH_{cym} + \beta_2 W_{cym} + \alpha_c + \alpha_m + \alpha_y + \varepsilon_{cym}. \tag{1}$$

Here, we aggregate all atmospheric measures over nine months because we are interested in the effects of pollution exposure in-utero, that is, during the nine months before birth. W includes meteorological and weather conditions for the same period, namely second order polynomials of temperature, wind speed and precipitation levels. The α indicators capture county (c), month (m) and year of birth (y) fixed effects. The inclusion of this set of weather controls and fixed effects ensures that BLH affects the educational outcomes of interest only through air pollution.

In Table 2 we assess whether BLH drives PM2.5 levels in the atmospheric dataset in the

[10]In our data, only 34 PM10 and 61 CO outdoor monitoring stations were active throughout the period 2000-2010.

years of interest for the educational outcomes. Standard errors are clustered at the county level. The first column looks at the period 2000-2010, in which children for whom we have information on secondary school track are born, which we define as the *Gymnasium* sample. Column 2 instead restricts the sample to the years 2002-2009, the period in which children for whom we have information on secondary school grades are born, which we define as the school grades sample.

Table 2: Effect of BLH on PM2.5

PM2.5 in-utero	(1)	(2)
Years	2000-2010	2002-2009
BLH in-utero	-0.504***	-1.04***
	(.021)	(.031)
Mean Dep. Var.	14.47	14.53
Counties	400	400
Observations	52800	38400
F-stat.	1037.9	741.9
R^2	0.87	0.88

The table shows the effects of BLH in-utero (in standard deviations) on the concentrations of PM2.5 in the same period at the county-month-year level in Germany. Column 1 includes all observations between 2000 and 2010, which is the period when the children in our main sample (*Gymnasium*) were born. Column 2 restricts the sample to the period 2002-2009, which is when the children in the school grades sample were born. The regression includes county, month and year of birth fixed effects and period-specific weather controls as described in equation 1. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

In line with existing literature, we see that atmospheric conditions, geographic patterns and seasonality (i.e. the right-hand side of equation 1) jointly explain a large share of the variations of PM2.5, and we find that BLH has a strong negative effect on PM2.5 levels: a one s.d. increase in the average BLH in-utero decreases average PM2.5 by 0.5-1 $\mu g/m^3$ in the corresponding period.

In addition to and alongside PM2.5, it is widely established that BLH strongly affects the concentration of many other pollutants, notably PM10 and CO, that may detrimentally affect fetal development (Schwartz, Bind, and Koutrakis, 2017; Godzinski and Castillo, 2021). In our setting, this means that BLH may affect educational achievement through its effect on various types of air pollution and their interactions. As discussed in subsection 3.2, we do not have access to reliable data on those other potentially relevant pollutants. Indeed, even the measured PM2.5 concentration is only imperfectly related to the actual exposure of the body of any single proband in the relevant spatial and temporal coordinates. This complicates the application of Instrumental Variable (IV) approaches to identify the channels through which prenatal BLH affects educational achievement. In addition, even if all pollutant concentrations are reliably measured, it would be an additional challenge for an IV strategy to define the most relevant weighted basket of pollutants.

Therefore, our baseline analyses and results concern the reduced form effect of BLH on educational outcomes. As noted above, this does not aim to estimate pollutant-specific dose-response functions, but rather to assess whether higher in-utero exposure to air pollution has discernible effects on educational achievement. This follows much of the related literature focusing on reduced form effects of atmospheric phenomena on socioeconomic outcomes (e.g. Jans, Johansson, and Nilsson, 2018; Molina, 2021). IV analyses using PM2.5 as the endogenous treatment variable are discussed in the Appendix of the paper.

4.2 Boundary layer height and educational outcomes

Exposure to air pollution is not random: individuals born in polluted areas differ from those born in less polluted areas along several unobservable characteristics. To address this concern, we leverage residual variations in BLH, as defined in equation 1, that generate exogenous variations in air pollution. Empirically, the identification of the effect of BLH on educational outcomes requires sufficient variation in the "exogenous" BLH. Figure A4 plots the distributions of the observed and of residualized values of BLH. The residuals are obtained after controlling for weather conditions and for county, month and year of birth fixed effects: the residual variation in BLH remains substantial (the standard deviation is 42, a decrease of one third compared to the baseline of 62) and drives the identification in our study.

The effect of BLH on educational achievement Y of student i, born in county c in month m in year y is retrieved by the following equations, which slightly differ for whether the student is enrolled in the academic track and for school grades:

$$Y_{icym} = \delta_1 BLH_{cym} + \delta_2 W_{cym} + \delta_3 X_i + \gamma_c + \gamma_m + \gamma_y + \nu_{icym}, \tag{2a}$$

$$Y_{icym} = \delta_1 BLH_{cym} + \delta_2 W_{cym} + \delta_3 X_i + \gamma_c + \gamma_m + \gamma_y + \gamma_s + \nu_{icym}. \tag{2b}$$

BLH is the average level of boundary layer height during pregnancy and W includes second order polynomials of temperature, wind speed and precipitation levels during the same period. X includes a set of individual and household level controls, namely child gender, migration background, birth order, maternal age at birth and parental education at birth, for which we set missing values to the modal values (secondary education for both mothers and fathers) and add dummies for missing values; in equation (2b) we also control for age in months and its squared. The γ indicators capture county (c), month (m) and year of birth (y) fixed effects; in equation (2b) we also include school track fixed effects (s, denoting lower, medium, higher track and *gesamtschule*), to control for the type of school attended by the student. Note that we use lower case y for year of birth and upper case Y for outcome variables. Standard errors are clustered at the county level. For school grades, the individuals that are surveyed both at age twelve and fourteen are weighted by a factor of 1/2. The effect of interest δ_1 is identified from variations in the average level of BLH in-utero between children born in the same county, netting out the average monthly and yearly trends.

To empirically strengthen the credibility of the exogeneity assumption for BLH, we check for the presence of a systematic correlation of BLH with the background household and child characteristics, that are included in the baseline model. Table A2 in the Appendix shows this for the two samples of interest; the coefficients on BLH are not statistically significant for any background controls, except for paternal tertiary education in the *Gymnasium* sample, for which the correlation is significant at the 10% level, but this can be expected by chance given the large number of coefficients tested.

5 Results

5.1 Baseline results

Table 3 shows the reduced form effects of in-utero exposure to pollution on our measures of educational attainment, namely the rate of transition to *Gymnasium* and school grades in secondary school. We find that a one standard deviation decrease in BLH decreases the likelihood of enrolment in the academic track by 3.7 percentage points, a sizeable effect considering the baseline share of students in *Gymnasium*.

The size of the coefficient should be carefully interpreted, as this outcome is unique to the German context and not straightforwardly comparable to more common measures of educational attainment such as standardized cognitive tests (Molina, 2021) and national school exams (Bharadwaj et al., 2017; Sanders, 2012). The most relevant study to benchmark our estimate is the study by Brehm et al. (2025), who show that the staggered implementation of Low Emission Zones (LEZ) in North-Rhine Westphalia, the most populated federal state in Germany, increased the rates of transition to the academic track by 1.0-1.7 percentage points.

The larger effect found in our study is plausible for two reasons. First, while their study focuses on the short to medium-term effects of the LEZ introduction (one to six years after implementation) for primary school students, we look at the long-term effects of pollution exposure during gestation, a period when the effects of pollution exposure are particularly harmful and potentially irreversible on key dimensions of fetal development. Second, while the implementation of LEZ reduced concentrations of NO_2 by 1.2-2.1 $\mu g/m^3$ and of PM10 by 0.6-1.3 $\mu g/m^3$, we find that a 1 standard deviation decrease in BLH in-utero (around 62 m) increases concentrations of PM2.5 by 0.5-1 $\mu g/m^3$. Compared to PM2.5, PM10 concentrations are larger and more volatile by definition, as these include larger and less harmful particles; therefore, for the same decrease in boundary layer height, it is plausible to expect larger variations in PM10 concentrations than those caused by the implementation of Low Emission Zones.

For secondary school grades, in columns 2 and 3, we do not find significant effects, suggesting no systematic differences in academic performance during the school year between children who were exposed to different levels of air pollution in-utero. A possible interpretation of this result is that prenatal pollution exposure influences educational attainment at the extensive margin, by affecting track allocation in the transition from primary to secondary school, but it does not significantly affect outcomes at the intensive margin, as captured by school grades within track. However, it should also be noted that school grades are relatively coarse and potentially noisy measures of academic performance, and may therefore fail to capture effects that could be detected using more rigorous and comparable assessments, such as standardized test scores or national school exams.

A potential issue for the interpretation of the effect of prenatal BLH on both the transition to the academic track and secondary school grades is that comprehensive schools are included as a single category in the data. Since these schools offer multiple tracks, including the academic one, we do not observe in the data the actual track attended by students. This can clearly affect the estimates of transition rates, but also those on the effect on school grades, as the school track fixed effects in the main specification do not capture the type of track attended in

Table 3: Boundary Layer Height and Educational Achievement

	(1)	(2)	(3)
	School track	School grades: age 12-14	
Dep. Var.	Gymnasium	German	Maths
BLH in-utero	0.0371**	0.0735	0.0626
	(.0179)	(.0491)	(.0583)
Mean Dep. Var.	0.43	4.33	4.27
Counties	373	346	346
Observations	5902	3247	3246

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium*, the academic track, and on school grades at age 12-14. All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equations (2a-2b). SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

a comprehensive school. In Table A3 we resrict the samples to children enrolled in one of the three classic tracks (*Hauptschule*, *Realschule* and *Gymnasium*). We see that the coefficient for the rate of transition to *Gymnasium* remains unchanged and the effects on the school grades remain not significant, indicating that the main results are not driven by differential patterns in comprehensive schools in terms of transition rates and school grades.

As noted in subsection 4.1, we considered an IV approach in which the in-utero average exposure to PM2.5 is the treatment variable. Here, the outcome is the academic track and the instrument is BLH. Estimation results are in the Appendix. Specifically, Table A4 shows the results from the IV approach (first stage in column 1 and IV in column 2) and the results from our main specification (column 3) in the three different samples of interest: the baseline sample, including children born in 2000-2010 and all school tracks in panel A; the sample including children born in 2000-2010 enrolled in one of the three classic tracks, but not in comprehensive schools in panel B; the school grades sample, including children born in 2002-2009 and enrolled in one of the three classic tracks in panel C. The first stage effect of BLH on PM2.5 in the samples is similar to the effect in the atmospheric dataset reported in Table 2, suggesting that there are no differences in terms of spatial composition across the different samples. The reduced form effect of BLH on the transition rate to *Gymnasium* is around 3.7 percentage points across samples, though it loses significance in panel C. Keeping in mind the aforementioned drawbacks of the IV approach in our setting, the IV results do confirm the substantial effect of prenatal exposure to pollution on the transition into the academic track.

5.2 Effect heterogeneity

In this subsection we assess heterogeneity of the effects with respect to various socio-demographic dimensions, namely gender, order of birth (whether the child is the first born or not), maternal and paternal education (tertiary education or less). The common framework to study effect heterogeneity of a treatment along a dimension simply consists of adding an interaction term to the baseline regression, which should indicate the presence of heterogeneous effects. However, not including the interaction of that dimension with the other covariates may severely bias the estimate of the main interaction effect (Feigenberg, Ost, and Qureshi, 2023). In our setting, where BLH is exogenous conditional on weather controls and location and time fixed effects, the ideal solution to causally interpret the interaction effect would be to interact the dimension of interest with weather controls and the set of fixed effects. However, this would imply the inclusion of a very large set of controls in an already very small sample; moreover, the interacted fixed effects would severely limit the identifying variation in the sample and lead to a significant loss of observations. To address the omitted variable bias while not significantly affecting the precision of the estimates, we add the interaction of the dimension of interest with the (standardised) weather controls. Importantly, the coefficients of the interactions of interest do not change when including the interaction with month and year fixed effects, but the standard errors largely increase, as expected.

Figure 1 plots the coefficients of interest from these regressions (Table A5 shows the point estimates of these regressions). Considering the demographic characteristics of the child, the point estimates of the interactions suggest that females are less impacted from a decrease in BLH (and a consequential increase in air pollution) than males; moreover, first born children seem to be less impacted than later born siblings by a lower air quality in-utero, which might indicate differential parental investment across siblings. The direction of both effects is in line with the literature on the differential parental investments by gender and parity of the child, but the effects are not significant. When considering parental education, we find that the negative effect of a decrease in BLH is almost completely offset by high maternal education: the negative effect of prenatal pollution for low-SES children is around five times larger than that for high-SES children. The figure shows a similar dynamics for paternal education, though the interaction effect is lower and not significant. Overall, the presence of a negative SES gradient is in line with the previous literature and suggests that higher parental education strongly compensates for

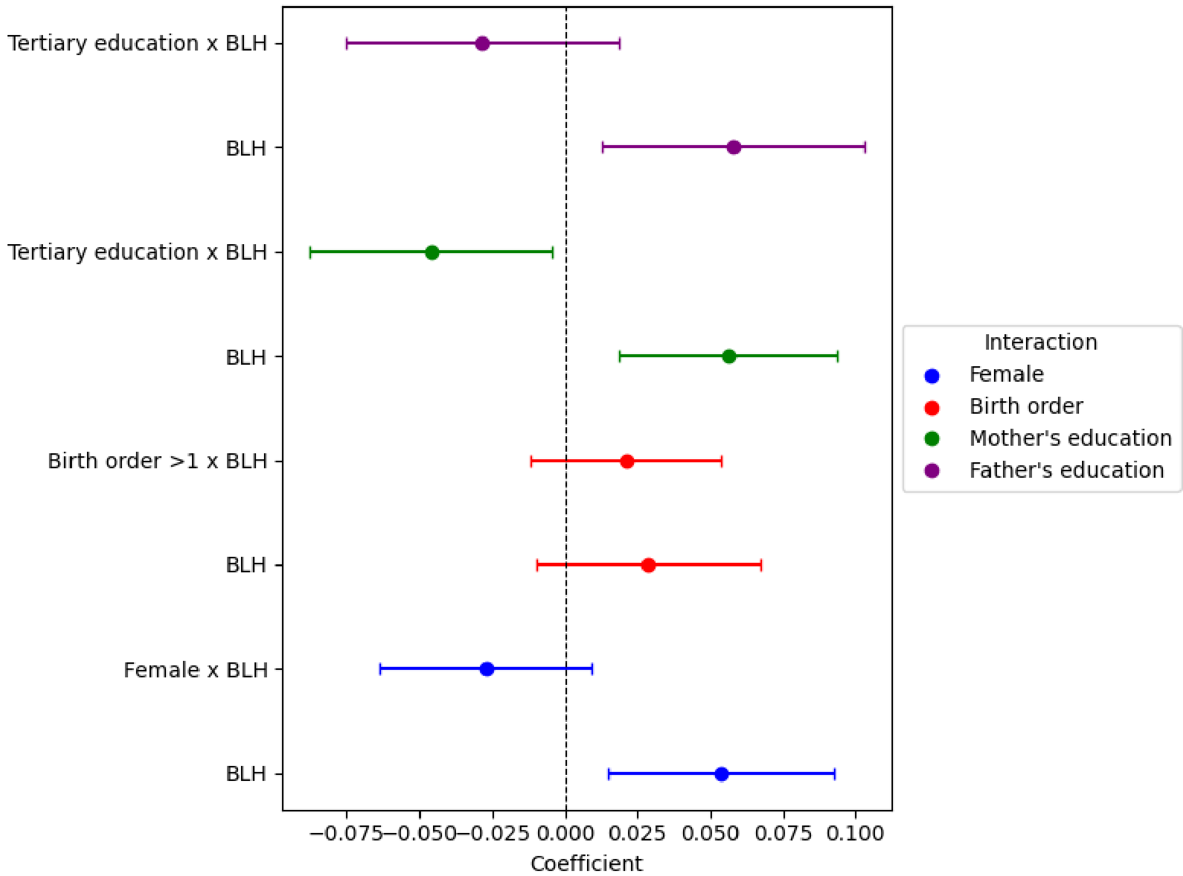

Figure 1: Effect Heterogeneity by Demographics and SES

The figure shows estimated coefficients of reduced form regressions of educational achievement (*Gymnasium*) on BLH during the in-utero period and interactions between BLH and sociodemographic characteristics of child and parents. Each color represents a different regression. The coefficients of BLH are the baseline coefficients. All regressions include county, month and year of birth fixed effects, parental and child characteristics and weather controls as described in equation (2a).

the adverse effects of prenatal pollution exposure (Voorheis et al., 2017; Bernardi and Keivabu, 2024; Thies, 2024).

Given the volatility in the effect of BLH on PM2.5 across different years as shown in Table 2, a legitimate concern is that BLH affects PM2.5 differently across different subsamples, and so that the heterogeneous effects that we find are not driven by the heterogeneous effects of air pollution on educational achievement but rather by the heterogeneous effects of BLH on air pollution. We directly check for this possibility by testing whether the effect of BLH on PM2.5 changes across the characteristics we are interested in: we find virtually no differences in the effect across subgroups, confirming that the effects we find are indeed driven by the heterogeneous effects of air pollution on educational achievement.

Since the level of boundary layer height is not systematically correlated with socioeconomic and demographic characteristics of the household, including parental education, this effect can be mainly attributed to the possibility of high SES households to remediate the effect of pollution exposure during the child's development rather than to the possibility to enjoy a better air quality in the first place. In other words, a higher parental education likely entails better financial means invested in the child's development and a higher awareness of the effects and the implications of exposure to air pollution.

In our setting, the strong mitigating effect of high parental education could be partially attributed to the higher relative importance of the final parental decision regarding the secondary school track allocation, as compared to households from lower education backgrounds, relative to other factors such as teacher recommendation and child's performance in primary school. In other words, the decision of highly educated parents on the track allocation may be less influenced by the teacher recommendation; alternatively, higher educated parents may influence the teacher's recommendation to align it with their preferences in the first place. While this hypothesis cannot be tested directly in the data, several studies in the German context suggest that the choice of secondary school track and the subsequent educational achievements of the child are strongly correlated with parental education (Waldinger, 2007; Dodin et al., 2024).

5.3 The role of parental involvement

The mitigating effect of parental education suggests that higher educated parents can remediate the adverse effects of prenatal pollution exposure more effectively than lower educated parents. One of the mechanisms explaining this socioeconomic gradient could be the differential parental response to the child's pollution exposure in terms of involvement during early childhood. In other words, higher educated parents could increase the frequency of "beneficial" activities during early childhood in response to higher prenatal pollution exposure, thus mitigating its adverse effect.

For the purpose of this study, we focus on maternal involvement and on the activities described in Section 3. Table A6 illustrates the baseline effect of parental involvement and of the separate activities on the likelihood of transition to *Gymnasium*: in column 1, we see that engaging activities are beneficial to the child, whereas passive or low-involving activities have a negative effect (marginally insignificant). Looking at the activities separately, column 2 shows that singing and reading frequently significantly increase the likelihood of transition to the academic track, while frequently watching tv has negative effects; finally, frequent painting and crafting activities do not significantly affect the educational trajectory of the child.

Having determined how maternal involvement is correlated with the educational achievement of the child, we assess whether it causally mediates the differential effect of pollution by parental SES. Table A7 shows that exposure to air pollution does not significantly affect the frequency of any of the activities of interest, regardless of the mother's education level, thus ruling out the mediation hypothesis. Therefore, mothers do not seem to adjust the type of involvement nor the frequency of the activities in response to variations in pollution exposure.

The absence of evidence on parental response to prenatal pollution is consistent with a setting like the German one, where pollution concentrations are relatively low and rarely give rise to major public health concerns. However, it may be the case that parents with a higher education carry out beneficial activities more frequently or are more actively involved than lower educated parents, independent of their children's exposure to pollution. Table A7 shows how parental education is correlated with the frequency of the activities at the mean level of BLH: compared to lower educated mothers, mothers with tertiary education carry out passively entertaining activities less frequently, while there is no significant difference in terms of engaging activities. Considering the activities separately, higher educated mothers tend to read and to sing songs with the child more frequently on one hand, and to paint and do crafts and watch tv less frequently on the other.

To understand how these maternal activities moderate the effect of prenatal exposure to pollution, we assess effect heterogeneity with respect to their frequency. Again, we consider heterogeneity both along the level of engagement of mothers, and separately for specific activities. The results are illustrated in Table 4. Also in this case, we address omitted variable bias by adding the interaction of maternal engagement or maternal activities with the weather controls. Therefore, the baseline coefficient on maternal activities can be interpreted as the effect at the mean level of BLH, precipitations, wind speed and temperature. Considering the first two columns, we find significant heterogeneous effects for high frequency of engaging activities and no significant heterogeneous effects for high frequency of passive activities. In particular, a high frequency of engaging activities of mothers with children strongly compensates for the adverse effect of prenatal pollution exposure. Put differently, the beneficial effects of maternal engagement are particularly relevant at high levels of pollution, and become less relevant as air quality increases. Conversely, a high frequency of passively entertaining, screen-based activities does not alter the effect of exposure to pollution. In other words, the negative baseline effect of frequently carrying out these activities does not change by the child's in-utero exposure to pollution. In line with the baseline effects of maternal involvement on the child's educational achievement, these results suggest that the quality of maternal involvement matters more than the actual time spent with the child.

While the first two columns provide evidence on aggregate measures of maternal involvement with the child, assessing the heterogeneous effects of pollution exposure by specific activities can provide insights on what activity mostly drives the effects in columns 1-2 and on how each activity moderates the effect of pollution. After controlling for the interaction of each activity with weather controls, we find that reading frequently with the child mitigates the negative effect of pollution exposure with similar magnitudes to the effects in column 1. The mitigating effect of reading is not surprising given that this activity loads predominantly on E_a (Table A1). For the other activities, we do not find evidence of heterogeneous effects, and also the estimates of the interaction coefficients are quite small, while the baseline effects of the activities on educational achievement are in line with the effects in Table A6. This suggests that high maternal involvement can effectively remediate the adverse impact of pollution especially through cognitively stimulating or educational activities like reading. Moreover, if we consider that higher educated parents tend to be more frequently involved in engaging and educational activities, particularly reading, differential parental engagement is one of the reasons underlying the socioeconomic gradient in the effect of prenatal pollution exposure on the likelihood of transition to the academic track.

As for the heterogeneity by sociodemographic characteristics, we test whether these results could be driven by heterogeneous effects of BLH on PM2.5 across subsamples. Also in this case we find that the effect of BLH on PM2.5 does not change across level of parental activities, thus confirming that the results in Table 4 reflect heterogeneous effects of air pollution on educational achievement by parental activities.

Table 4: Heterogeneous Effects by Parental Activities

Gymnasium	(1)	(2)	(3)	(4)	(5)	(6)
BLH in-utero	.107***	.0577	.0624*	.0715**	.0494	.1052***
	(.0408)	(.037)	(.0352)	(.0341)	(.0381)	(.0405)
E_a	.0482**					
	(.0228)					
E_a x BLH	-.0637**					
	(.0323)					
P_a		-.0334				
		(.0221)				
P_a x BLH		.0157				
		(.0301)				
Singing (high freq.)			.0594***			
			(.0212)			
Singing (high freq.) x BLH			.0152			
			(.0274)			
Painting (high freq.)				.0283		
				(.0207)		
Painting (high freq.) x BLH				-.0163		
				(.0249)		
Watching tv (high freq.)					-.0303	
					(.0195)	
Watching tv (high freq.) x BLH					0.0124	
					(.0315)	
Reading (high freq.)						.0575***
						(.0215)
Reading (high freq.) x BLH						-.068**
						(.0317)
Mean Dep. Var.	0.46	0.46	0.46	0.46	0.46	0.46
Counties	291	291	301	302	301	302
Observations	2373	2373	2585	2586	2587	2589

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium* interacted with indicators of maternal engagement (columns 1-2) and with a set of maternal activities (columns 3-6). Each regression controls for the interaction of the dimension of interest with weather controls. All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equation (2a). SE clustered at county level. *** p<0.01, ** p<0.05, * p<0.1

5.4 Robustness checks

Table 3 shows that a decrease in boundary layer height and a consequential increase in pollution concentration in-utero decreases the likelihood of transitioning to the academic track in secondary school. In the Appendix, we test the robustness of this result to alternative samples (Table A8) and to alternative specifications (Table A9).

In our main specification, we do not impose a minimum number of observations per county. However, in this fixed effects model, counties with very few observations and high variance in the dependent and independent variables could potentially drive our result. To reduce the influence of outliers, in line with previous studies (Molina, 2021; Thies, 2024), in columns 1 and 2 of Table A8 we restrict the sample to counties with at least 10 or 20 observations, respectively. The coefficients are larger and more significant than in the baseline model, as expected. In column 3 we exclude the survey year 2020, as the outburst of the pandemics may have heavily affected trends in the outcome: the coefficient is slightly lower but remains significant.

Column 1 of Table A9 replicates the reduced form model in equation (2a) excluding background household and child characteristics, to check whether the main result is driven by the inclusion of the set of socioeconomic and demographic controls. In column 2, the coefficient is virtually unchanged when excluding the quadratic terms from the set of weather controls. In column 3 we add one lead and one lag (average value of the nine months before pregnancy and of the nine months after birth) of BLH and of the weather variables to the main specification. Given the temporal auto-correlation of the weather variables and of BLH, omitting atmospheric variables from before pregnancy and after birth could result in their effects loading onto the coefficient of interest. The coefficient on the lead and on the lag is not significant, but remains significant for the in-utero period. This is further confirmed in column 4, where we regress the dependent variable only on the lag and its correspondent weather controls. The absence of any effect, both in terms of significance and size, in the period before pregnancy confirms that the effect of pollution exposure on educational achievement operates only through the effects of pollutants on the fetus' neurocognitive and physical development. In column 5 we add state by year-of-birth fixed effects in the main model to address the possibility that the result is driven by regional trends in the outcome, which could be related to reforms or changes of the school system at the state level during the period of interest. Also in this case, the coefficient is significant and similar in magnitude to the estimate of the main specification. Similarly to columns 5, in column 6 we expand the main model by adding state by month-of-birth fixed effects to address the concern that age of school entry, which differs across states, is not properly accounted for in the main model. There is suggestive evidence that month of birth can influence early educational attainment through age of school entry, with older students peforming better in terms of grades and track allocation (Patrick A. Puhani and Andrea Maria Weber, 2007; Patrick A. Puhani and Andrea M. Weber, 2008). This would bias the estimate of interest if parents could select the month of birth of the child and if this was in turn correlated with pollution exposure. While in our framework variations in pollution are exogenous to seasonal patterns by construction, the coefficient of interest remains significant when expanding the set of fixed effects.

6 Conclusion

This paper examines the effect of prenatal exposure to air pollution on educational achievement in Germany, assessing whether this effect changes depending on the socioeconomic background of the household and testing how maternal involvement and activities during early childhood moderate the impact of pollution. Educational achievement is measured by school grades at ages twelve and fourteen and by the rate of transition to the academic track (*Gymnasium*) in secondary school. Due to the German early and rigid tracking system, characterized by a low mobility across tracks, the chosen track for secondary school has relevant implications for the academic and the professional trajectory of the child (Dustmann, 2004).

To address potential endogeneity in the exposure to air pollution, we leverage exogenous variations in the height of the planetary boundary layer (BLH), an atmospheric variable strongly affecting pollution concentrations on the ground.

We find that an increase in pollution exposure during gestation significantly decreases the likelihood of transitioning to the academic track, with the effect being concentrated among children from less educated families. This socioeconomic gradient cannot be explained by a differential response to pollution exposure in terms of parental involvement. However, maternal involvement moderates the impact of pollution: in particular, a high frequency of active and engaging activities with the child during early childhood effectively remediates the adverse effects of pollution exposure; this gradient is mostly driven by cognitively stimulating activities like reading with the child. Conversely, we find no evidence that a high frequency of passively entertaining activities, such as screen-based activities, moderates the effect of pollution exposure. This suggests that the quality of the time spent with children matters more than the quantity, also during early childhood. Considering that mothers with tertiary education tend to be more actively engaged with children than lower educated mothers, these findings also suggest that differential parental involvement can partly explain the socioeconomic gradient in the effect of prenatal pollution exposure on educational achievement.

These results offer new insights for the evaluation of the long-term effects of prenatal pollution exposure. On the one hand, a high socioeconomic status, as measured by parental education, significantly remediates the adverse effects of pollution on educational achievement. This leaves the opportunity for socially equitable policies, such as targeted subsidies or early-life programs for children of lower educated households, to limit the vulnerability of disadvantaged children and to reduce the socioeconomic gap with higher educated households.

On the other hand, engaging parental activities that educate and cognitively stimulate the child, can also effectively remediate the impacts of pollution exposure, particularly for lower educated households. This highlights the importance of the quality of parental involvement during the child's early development, which is not unequivocally determined by parental education and socioeconomic status.

In this regard, disentangling the relative roles of parental involvement and parental SES is an important avenue for future research on the long-term impacts of adverse prenatal exposures.

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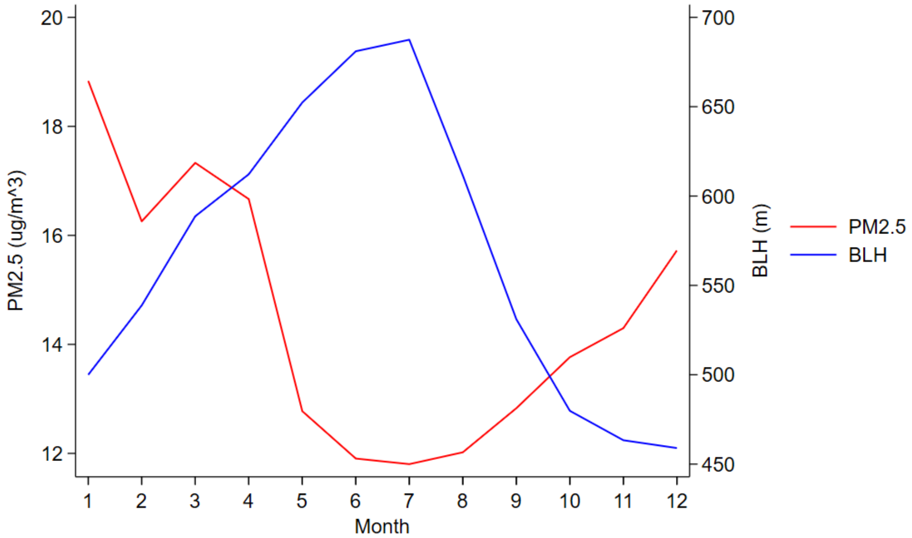
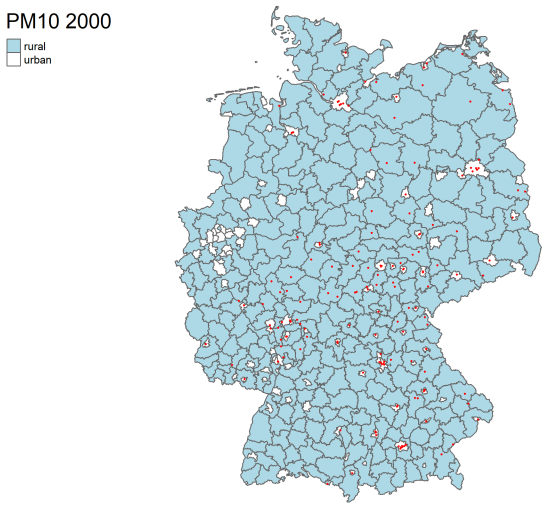
Appendix

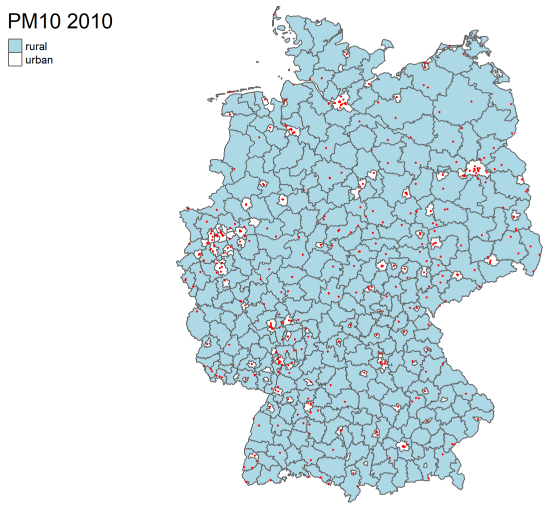
Figure A1: Correlation Between BLH and PM2.5 Over Time



The figure shows the inverse relation of the monthly values of BLH and PM2.5 averaged over the years 2000-2010.



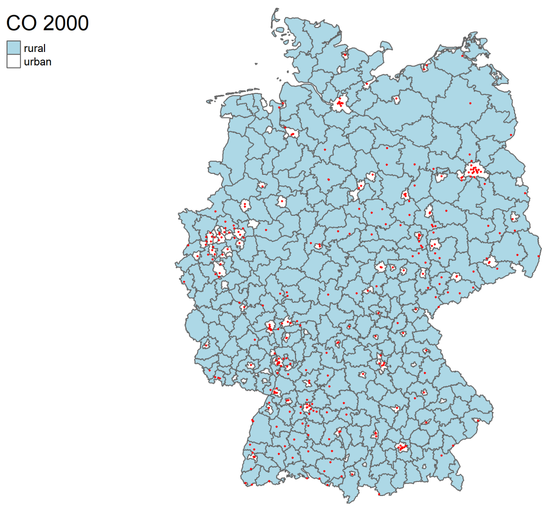
(a)



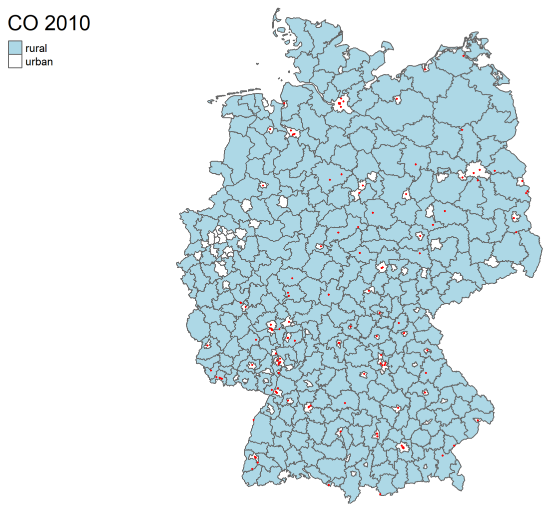
(b)

Figure A2: Distribution of PM10 monitoring stations in Germany, 2000 vs 2010

The red dots in the figure indicate the active outdoor stations in that year across German counties (white for urban and blue for rural).



(a)

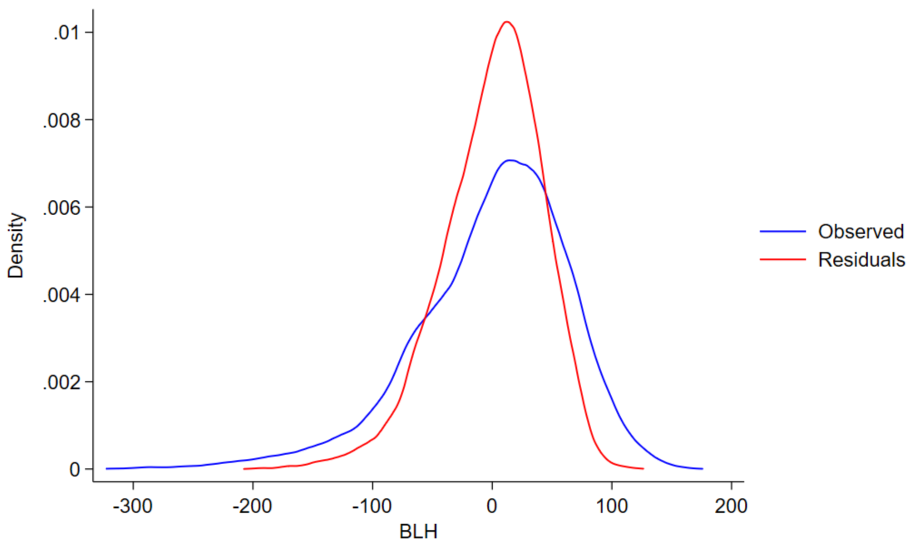


(b)

Figure A3: Distribution of CO monitoring stations in Germany, 2000 vs 2010

The red dots in the figure indicate the active outdoor stations in that year across German counties (white for urban and blue for rural).

Figure A4: Observed and Residualized Values of BLH



The figure plots the distribution of the observed BLH (centered around zero) and of the residualized BLH. The residuals are obtained from the regression of BLH on period-specific weather conditions and county, month and year of birth fixed effects, with SE clustered at the county level.

Table A1: Maternal Activities: Factor Loadings

	Factor 1 (E_a)	Factor 2 (P_a)
Ages 1, 3, 6:		
Singing	*0.76*	-0.18
Painting	*0.72*	0.17
Watching tv	0.06	*0.76*
Reading	*0.70*	-0.33
Age 6:		
Playing cards	*0.59*	0.28
Computer games	0.00	*0.77*
Cultural trips	*0.32*	0.09
Obervations	2473	
Correlation	0.11	

The table reports factor loadings of the maternal activities of interest obtained from a principal component analysis and an oblique rotation. Values in italics indicate the factor with the higher loading for the activity.

Table A2: Falsification checks

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dep.Var	MAB	Migration Background	Mother: No HS	Mother: HS	Mother: Tertiary	Father: No HS	Father: HS	Father: Tertiary
				Panel A: Gymnasium Sample				
BLH in-utero	-0.218	-0.01	-0.016	0.023	-0.006	-0.017	-0.025	0.041*
	(.223)	(.018)	(.014)	(.02)	(.018)	(.014)	(.026)	(.024)
Observations	5902	5902	5885	5885	5885	4776	4776	4776
				Panel B: School Grades Sample				
BLH in-utero	-0.465	0.017	-0.03	0.044	-0.013	-0.03	-0.016	0.045
	(.32)	(.029)	(.023)	(.031)	(.029)	(.021)	(.037)	(.036)
Observations	3247	3247	3241	3241	3241	2751	2751	2751

The table shows the effects of BLH in-utero (in standard deviations) on a set of household and child characteristics for the two samples of analysis. MAB (Mother's age at birth) is measured in years. All regressions include county, month and year of birth fixed effects, child gender and period-specific weather controls as described in equation 2a-2b. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

Table A3: Main Results, Only Classic Tracks

	(1)	(2)	(3)
	School track	School grades: age 12-14	
Dep. Var.	Gymnasium	German	Maths
BLH in-utero	0.038*	0.0357	0.0643
	(.0198)	(.0577)	(.0669)
Mean Dep. Var.	0.56	4.36	4.30
Counties	373	333	333
Observations	4500	2746	2745

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium*, the academic track, and on school grades at age 12-14, restricting the samples to children who enrolled in one of the three classical tracks(no *gesamtschule*, vocational or other). All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equations (2a-2b). SE are clustered at the county level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A4: BLH and Gymnasium: IV and Reduced Form Effects in Different Samples

	(1) First Stage: PM2.5	(2) IV: Gymnasium	(3) Reduced form: Gymnasium
	Panel A: Full Sample		
BLH in-utero	-0.55***	-0.067**	0.037**
	(.046)	(.032)	(.018)
Mean Dep. Var.	14.88	0.43	0.43
Counties	373	373	373
Observations	5902	5902	5902
	Panel B: Only Classic Tracks		
BLH in-utero	-0.51***	-0.074*	0.038*
	(.05)	(.038)	(.0198)
Mean Dep. Var.	14.8	0.56	0.56
Counties	357	357	357
Observations	4500	4500	4500
	Panel C: School Grades Sample		
BLH in-utero	-0.99***	-0.038	0.037
	(.087)	(.031)	(.03)
Mean Dep. Var.	14.89	0.59	0.59
Counties	308	308	308
Observations	2644	2644	2644

The table compares the IV effect of PM2.5 (column 2) with the reduced form effect of BLH (column 3) on *Gymnasium* (column 1 shows the first stage effect of BLH on PM2.5). Panel A shows results for the full Gymnasium sample, children born in 2000-2010. in panel B we restrict the sample to children who enrolled in one of the three classic tracks (i.e. Hauptschule, Realschule and Gymnasium), children born in 2000-2010. In panel C we run the same models in the school grades sample who enrolled in one of the three classic tracks, children born in 2002-2009. All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equations (2a). SE are clustered at the county level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A5: Effect Heterogeneity by SES

Gymnasium	(1)	(2)	(3)	(4)
BLH in-utero	0.0538***	0.0286	0.0561***	0.0579**
	(.0197)	(.0196)	(.0191)	(.0228)
Female x BLH	-0.0272			
	(.0186)			
Birth order >1 x BLH		0.021		
		(.0167)		
Mother: Tertiary x BLH			-0.046**	
			(.0212)	
Father: Tertiary x BLH				-0.0284
				(.0239)
Mean Dep. Var.	0.43	0.43	0.43	0.46
Counties	373	373	373	357
Observations	5902	5902	5885	4776

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium* interacted with gender, birth order (first born or higher parity) maternal and paternal education (tertiary education or less). Each regression controls for the interaction of the dimension of interest with weather controls. All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equation 2a. SE are clustered at the county level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table A6: Maternal Activities and Gymnasium

Gymnasium	(1)	(2)
E_a (high)	0.0537**	
	(.0238)	
P_a (high)	-0.0362	
	(.023)	
Singing (high freq.)		0.048**
		(.0221)
Painting (high freq.)		0.0144
		(.0214)
Watching tv (high freq.)		-0.0319
		(.0202)
Reading (high freq.)		0.0409*
		(.0216)
Mean Dep. Var.	0.46	0.46
Observations	2373	2575

The table shows the baseline effects of maternal activities on the likelihood of transition to *Gymnasium*. In column 1, these are measured as high relative involvement in engaging activities and in passive activities. In columns 2, we focus on the subset of activities measured at ages 1, 3 and 6. Both regressions include county, month and year of birth fixed effects, parental and child characteristics as described in equation 2a, and exclude BLH and weather controls. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

Table A7: Maternal Activities and Boundary Layer Height

	(1)	(2)	(3)	(4)	(5)	(6)
High Frequency of:	E_a	P_a	Singing	Painting & Crafts	Watching TV	Reading
BLH in-utero	0.0209	-0.0338	-0.0177	0.0397	-0.044	0.003
	(.0393)	(.0351)	(.0376)	(.0344)	(.039)	(.0377)
Mother: Tertiary	0.0264	-0.0985***	0.0413	-0.0517*	-0.0618**	0.1327***
	(.0296)	(.027)	(.0272)	(.03)	(.0294)	(.0269)
Tertiary x BLH	0.0253	-0.0086	0.015	-0.0019	-0.0233	0.0044
	(.022)	(.0228)	(.0267)	(.0246)	(.0255)	(.0226)
Mean Dep. Var.	0.54	0.45	0.58	0.53	0.56	0.61
Counties	291	291	301	302	301	302
Observations	2365	2365	2577	2578	2579	2581

The table shows the effects of BLH in-utero (in standard deviations) by maternal education status (tertiary education or less) on the frequency of engaging or passive maternal activities(columns 1-2), and on the frequency of a set of maternal activities (columns 3-6). All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equation 2a. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

Table A8: Robustness: Alternative Samples

Gymnasium	(1)	(2)	(3)
BLH in-utero	0.0469**	0.0497**	0.0301*
	(.0184)	(.0199)	(.0181)
Minimum Obs. per county	10	20	All
Years	All	All	No 2020
Mean Dep. Var.	0.43	0.44	0.42
Counties	245	140	373
Observations	5305	4143	5453

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium*, using different samples from the baseline sample of equation 2a. Columns 1 and 2 restrict the sample to counties with at least 10 and 20 observations, respectively. Column 3 excludes survey year 2020 from the analysis. All regressions include county, month and year of birth fixed effects, parental and child characteristics and period-specific weather controls as described in equation 2a. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.

Table A9: Robustness: Alternative Specifications

Gymnasium	(1)	(2)	(3)	(4)	(5)	(6)
BLH in-utero	0.0444**	0.0373**	0.0471**		0.0389*	0.0471**
	(.0206)	(.0175)	(.0236)		(.0213)	(.0187)
BLH prenatal			-0.0027	-0.0079		
			(.0209)	(.0182)		
BLH postnatal			-0.0198			
			(.023)			
Mean Dep. Var.	0.43	0.43	0.43	0.43	0.43	0.43
Counties	373	373	368	369	373	373
Observations	5902	5902	5542	5642	5895	5900
Specification	No SES controls	Linear weather	Ext. Weather controls	1 Lag BLH	Year*region FE	Month*region FE

The table shows the effects of BLH in-utero (in standard deviations) on the likelihood of transition to *Gymnasium*, using different specifications from the baseline regression in equation 2a. In column 1 we do not include the set of child and household background characteristics X. In column 2 we do not include weather controls in quadratic form. In column 3 we add one lead and one lag (nine months average) of BLH and of second order weather controls. In column 4 we run the same regression as column 3 but only keeping the lag of BLH and the correspondent weather controls. In column 5 and 6 we expand the set of fixed effects by including year of birth by state and month of birth by state fixed effects, respectively. SE are clustered at the county level. *** p<0.01, ** p<0.05, * p<0.1.