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What Do We Know About Short- and Long-Term Effects of Early-Life Exposure to Pollution?

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child, environment, human capital, health, latent, avoidance behavior

Abstract

Evidence shows that pollution exposure early in life is detrimental to near-term health, and an increasing body of evidence suggests that early-childhood health influences health and human capital outcomes later in life. This article reviews the economic research that brings these two literatures together. We begin with a conceptual model that highlights the core relationships across the life cycle. We then review the literature concerned with such estimates, focusing particularly on identification strategies to mitigate concerns regarding endogenous exposure. The nascent empirical literature provides both direct and indirect evidence that early-childhood exposure to pollution significantly impacts later-life outcomes. We discuss the potential policy implications of these long-lasting effects and conclude with a number of promising avenues for future research.

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1. INTRODUCTION

The protection of human health is a principal motivation for environmental regulation around the world. Children are particularly vulnerable to environmental exposures because their immune and other bodily systems are still developing and they often engage in behaviors that increase their exposure to toxic chemicals and organisms; e.g., they spend more time outside than adults do (Makri et al. 2004, Schwartz 2004, Bateson & Schwartz 2007, EPA 2013). Rapid cell division and an intense phase of epigenetic programming make the prenatal and immediate postnatal period an especially sensitive one (Holt 1998, Gluckman et al. 2008, Baccarelli & Bollati 2009). As such, the protection of children has become a driving force behind many environmental regulations.[1]

The impacts of early-life pollution exposure are of interest for nonhealth reasons as well. Early-life health affects long-term outcomes, including human capital accumulation, labor force participation, and earnings (see Almond & Currie 2011a,b for a review of this literature). Thus, the marginal returns to regulations that protect children may be both large and rather diffuse in that they affect many outcomes.[2]

In addition to broadening the focus beyond health, economists have made two important methodological contributions to the study of pollution impacts on children. First, economists have developed a conceptual framework for considering the effects of pollution within the larger framework of health production and investments. The framework implies, for example, that a lifetime of investments may strengthen or attenuate the pure biological insults experienced early in life. It also highlights that optimizing behavior, through residential sorting, can lead to nonrandom assignment of pollution. For example, as discussed further below, individuals with higher incomes are both less likely to raise their families in areas of poor environmental quality and more likely to make greater investments in their children's health. Failing to account for the correlation of higher health investments with living in an area with better environmental quality biases estimates of the effects of pollution.

Similarly, an optimizing framework leads to the consideration of avoidance behavior. Because the consequences of toxic exposures are costly, particularly to children, parents may engage in activities to prevent them. Avoidance behavior can muddy the measurement of biological effects in epidemiological research. Ignoring avoidance behavior can also lead to significant underestimation of the social welfare costs of pollution because a narrow focus on the costs of morbidity and mortality excludes the costs of avoidance activities (Courant & Porter 1981, Harrington & Portney 1987, Bartik 1988).

A second, and related, contribution in light of concerns regarding endogenous exposure to pollution is the use of quasi-experimental techniques to develop causal estimates of the effects of early-life pollution. The shorter possible exposure period and more limited geographic mobility of children allow quasi-experimental methods to more easily determine the effects of pollution on children relative to adults. Such causal inference has enabled the detection of effects at markedly low levels of pollution.

This article reviews the recent economic literature on the effects of early-life exposure to pollution. We focus primarily on air pollution because it has received the most attention in the literature, largely due to greater data availability. The remainder of the article is organized as

[1]In the United States, for example, Executive Order 13045 directs the EPA and other federal agencies to "ensure that its policies, programs, activities, and standards address disproportionate risks to children that result from environmental health risks or safety risks" (Clinton 1997).

[2]Large returns to early-life interventions have been found in a number of settings outside of environmental health (Schweinhart et al. 1993, 2005; Heckman 2000; Currie 2001).

follows. The next section describes the contribution of economics to our understanding of the impacts of early-life pollution exposure. We begin with a conceptual model, followed by a discussion of identification and welfare. Section 3 provides a structured review of the literature that organizes papers into common themes. Section 4 offers some concluding remarks and suggestions for future research.

2. WHAT DO ECONOMISTS BRING TO THE TABLE?

2.1. Conceptual Model

In this section, we develop a simple three-period model that builds upon earlier work on human capital accumulation and investments (Grossman 1972, Cunha & Heckman 2007, Almond & Currie 2011a,b) to highlight the salient features that link pollution and birth outcomes to health and human capital later in life.

Our framework divides life into three distinct stages: early childhood, late childhood, and adulthood. To fix ideas, one can view early childhood as beginning in utero and ending at age 5. Late childhood would comprise the school years, and adulthood can be viewed as the post-schooling period when people have typically entered the labor force. For simplicity, we model the human capital production function of a representative individual and abstract from the endogeneity of pollution exposure, although we return to this problem in the next section (Neidell 2009, Currie et al. 2011, Graff Zivin et al. 2011).[3]

Assume that early-childhood (E) human capital H_E is dependent on early-childhood pollution exposure P_E and time-invariant family characteristics X, such as genetics:

$$H_E = f_E(P_E, X). \tag{1}$$

Late-childhood (L) human capital H_L depends on late-childhood pollution exposure P_L and on the human capital accumulated during early childhood. Importantly, families can make investments I_L in their child that influence the legacy of those early-childhood outcomes. Those investments depend upon realizations of human capital in the first stage of life.

$$H_L = f_L\big(I_L(H_E), P_L\big). \tag{2}$$

Finally, assume that adult (A) outcomes H_A depend on both early- and late-childhood human capital. Given our focus on children, we ignore adult exposure to pollution and investments in human capital such that adults in our model should be viewed as fully formed. Human capital in adulthood is broadly construed to reflect the fact that pollution can affect cognitive attainment and earnings as well as health (Graff Zivin & Neidell 2013).

$$H_A = f_A(H_E, H_L). \tag{3}$$

Equations 1–3 imply that the impacts of early-childhood pollution exposure on adult human capital depend on the short-run effects of such exposure as well as on the propagation of those effects through the rest of the life cycle. These pathways are easily shown by taking the total derivative of Equation 3:

[3]Individuals may differ in their susceptibility to pollution for a variety of reasons apart from the explicit differences by stage of life that we attend to here. This heterogeneity affects the gradient between childhood and adult outcomes, but the basic insights from the model remain the same.

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$$\frac{dH_A}{dP_E} = \frac{\partial f_A}{\partial H_E}\frac{\partial H_E}{\partial P_E} + \frac{\partial f_A}{\partial H_L}\frac{\partial H_L}{\partial P_E}. \tag{4}$$

P_E (or P_L) may also have a direct, latent effect on H_A, which does not act through changes in H_E or in H_L. For the time being, we ignore the partial derivatives of H_A with respect to P_E and P_L, although we return to the question of latent effects below.

Our model of human capital accumulation can be used to illustrate several points regarding childhood exposure to pollution. As discussed above, it is reasonable to assume that the early-childhood period is one of greater sensitivity to pollution. The nine months in utero are a critical period for physiological development, and an increasing body of evidence suggests that fetal programming can be adversely impacted by toxic exposures (Barker 1990, Bateson & Schwartz 2007, Almond & Currie 2011a,b). All else equal, this evidence suggests that an equal dose of pollution has a bigger effect (in absolute value) in early childhood:

$$\left|\frac{\partial H_E}{\partial P_E}\right| > \left|\frac{\partial H_L}{\partial P_L}\right| \ \forall \ P_E = P_L. \tag{5}$$

In addition to greater contemporaneous health effects, early-life exposures can result in latent health impacts. In particular, pollution may have epigenetic effects—permanent alterations in gene expression—that can negatively impact intellectual growth and maturity later in life (Petronis 2010). Someone with latent epigenetic damage might initially appear to be in perfect health so that the following might be observed:

$$\left|\frac{\partial H_E}{\partial P_E}\right| = 0 \text{ and } \left|\frac{\partial H_A}{\partial P_E}\right| > 0. \tag{6}$$

The long potential latency period between exposure and the outcomes of interest also provides ample opportunity for effects to be amplified or dampened. Self-productivity and dynamic complementarities in health and learning, whereby capabilities beget capabilities in a multistage framework, suggest that early health shocks are multiplied over the life cycle (Cunha & Heckman 2007). The early manifestation of health and cognitive deficits may induce parental (dis) investments in early childhood that also impact later-life outcomes. Whether parents compensate for poor endowments at birth by increasing investments in those children or reinforce poor endowments by directing their efforts toward children with better prospects is an open empirical question in the literature (Behrman et al. 1994, Datar et al. 2010). If we expand the last term of Equation 4 above, the role of these investments can be made more explicit:

$$\frac{dH_A}{dP_E} = \frac{\partial f_A}{\partial H_E}\frac{\partial H_E}{\partial P_E} + \frac{\partial f_A}{\partial H_L}\left(\frac{\partial f_L}{\partial I_L}\frac{\partial I_L}{\partial H_L}\frac{\partial H_L}{\partial P_E}\right). \tag{7}$$

If we assume that the effects of pollution exposure are detrimental, self-productivity and dynamic complementarities imply that $\frac{\partial H_L}{\partial P_E}$ is large and negative—early deficits compound over the life cycle such that the impacts later can be quite large. Compensatory investments correspond to the case in which $\frac{\partial I_L}{\partial H_L}$ is negative, whereas reinforcing ones imply that this term is positive.

The principal value of Equation 7 is conceptual. Data limitations imply that all empirical investigations in this area paint a partial picture of this total derivative. Nonetheless, the equation underscores the connections across a wide range of empirical literatures within economics, including the environmental, education, labor, and health fields. This basic model also highlights the

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policy importance of the question addressed in this review. If the legacy effects of early pollution exposures are large, then even modest interventions to protect young children may have profound impacts on societal well-being and future economic growth. Of course, such benefits would have to be weighed against the costs of any regulatory efforts to protect children, and a proper welfare calculation should incorporate the costs borne by households seeking to avoid pollution and/or to compensate for its effects.

2.2. An Emphasis on Identification

Whereas the conceptual model just described has intentionally eschewed concerns about the endogeneity of pollution exposure, empirical economic studies on the effects of the environment on child health have not. Endogeneity can arise through two primary channels. The first is Tiebout sorting (Tiebout 1956), through which people vote with their feet by choosing residential locations on the basis of area characteristics, such as pollution levels or attributes coincidentally correlated with pollution levels. A growing body of empirical evidence suggests that sorting based on environmental quality is indeed a major factor affecting residential location. For example, Banzhaf & Walsh (2008) find that high-income families tend to move away from highly polluted areas, and Currie (2011), Currie & Walker (2011), and Currie et al. (2011) find that improving environmental quality in an area increases the share of pregnant women who are white and college educated. As a result of this sorting, areas with higher levels of pollution may also have other unobserved characteristics correlated with health, suggesting that omitted variable bias is likely to confound estimates.[4]

The second source of endogeneity arises from avoidance behavior. If individuals take actions to protect their children's health when pollution is high, these actions lead to nonrandom assignment of ex post pollution exposure. These kinds of actions require knowledge of pollution levels, either through experiential changes in health or, as may be more likely for younger children, through publicly provided information. The dissemination of pollution information to the public is mandated in many large cities and is often accompanied by recommended strategies for pollution avoidance, such as staying indoors or shifting activities to times of the day when pollution is expected to be lower.

Because avoidance behavior is an ex post decision—it occurs in response to realized pollution levels—its omission from analysis does not introduce a bias per se in estimates but rather affects the interpretation of estimated relationships. Estimates that account for avoidance behavior uncover the direct biological effect of pollution on health ($\partial H_A/\partial P_E$). Estimates that do not account for avoidance measure a reduced form effect of pollution on health, which consists of the biological effect plus the degree to which avoidance behavior (A_B) is successful in averting detrimental health effects ($dH_A/dP_E = \partial H_A/\partial P_E + \partial H_A/\partial A_B \cdot \partial A_B/\partial P_E$). Both estimates can be used to monetize the benefits from improvements in environmental quality, so the focus of estimation depends on the research question.

Economists have addressed endogeneity concerns with quasi-experimental techniques such as finding natural experiments that result in unexpected shocks to environmental quality. These shocks can be driven by government regulation (such as the Clean Air Acts in the United States), by unexpected changes in industrial production (such as strikes and plant closings), or by catastrophic events (such as temperature inversions and wildfires). Another approach consists of

[4]We also note that pollution, rather than people, may sort, whereby polluting industries locate in areas with lower land prices, which also tend to be areas with residents of lower socioeconomic status.

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exploiting high-frequency variability in pollution over short periods of time in conjunction with local area fixed effects, under the assumption that sorting in response to environmental changes occurs more slowly than health changes. A final approach consists of within-family designs, such as sibling comparisons, which hold fixed many unobserved characteristics common to children from the same family.

Although each approach has its advantages, important limitations must be recognized. For example, although an unexpected productivity shock can affect air pollution, it can also directly affect health through job losses or through the loss of health insurance (Sullivan & Von Wachter 2009). And the more that time elapses from the time of the shock, the greater is the probability that residential sorting complicates the picture. Natural experiments also do little to directly address ex post avoidance behavior. Despite these limitations, we show below that the weight of the evidence suggests that early-life exposure to pollution has negative long-term effects.

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3. LITERATURE REVIEW

Some of the earliest work by economists on the relationship between pollution and children's health is in chapter 8 of the seminal book by Lave & Seskin (1977). Their work highlighted the association between air pollution in US cities and infant mortality and spawned a huge literature in both public health and economics on the subject. Although early studies were necessarily correlational in nature, increases in data availability and advances in econometric techniques have led to tremendous changes in this literature, as highlighted at the beginning of this article. These advances have had a tremendous impact on the magnitude of estimates. Lave & Seskin estimate an elasticity of the dose-response function between particulates and infant mortality that ranges from 0.04 to 0.07. Two more recent studies with comparably defined variables (Chay & Greenstone 2003a,b; described below) estimate elasticities ranging from 0.3 to 0.45, an order of magnitude higher.

In this review, we limit our attention to the quasi-experimental papers that exploit these data and econometric revolutions to examine this relationship between pollution and children's health in a causal framework. **Tables 1** to **4** (see below) summarize this literature with respect to air pollution—the most reliably recorded measure of environmental quality. A general feature of this literature is that, although impacts are often attributed to a single pollutant, emissions of many pollutants tend to be highly correlated and may come from the same sources. For example, an analysis of the effect of carbon monoxide (CO) exposure on birth weight may really be measuring the effect of automobile exhaust, which includes particulate matter, nitrogen oxides, and other chemicals in addition to CO. Even analyses based on multipollutant models rarely have measures of all relevant emissions. That all pollutants are emitted from the same source may not matter from a policy perspective but certainly limits generalizability across settings.

3.1. Long-Term Effects of Air Pollution

Table 1 shows that relatively few studies make a direct connection between childhood exposure to pollution and long-term outcomes such as educational attainment and earnings. The small number of studies is largely due to limitations in data availability: Data that allow for the linkage of adult outcomes with childhood environmental quality are rare. In the absence of such data, some researchers employ a cohort approach to exploit differences between cohorts of children born just before and after an environmental shock. This approach generally works best in the case of a large shock.

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Table 1 Studies of air pollution and long-term outcomes

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Almond et al. (2009); Sweden; Chernobyl disaster	An OLS approach is used to measure outcomes of those exposed against a number of comparison groups. Additionally, a D-in-D approach is used to examine compensatory behavior effects on affected children. Both approaches include a wide set of controls.	Data on child-level outcomes (birth, health, school, and hospitalizations) of Swedish birth cohorts from 1983 to 1988 are linked with radiation data collected from ground monitors and from a country-wide aerial survey of ground deposition in 1986. More than 500,000 observations are used with the aerial exposure data, and ~170,000 observations are used when monitor levels are examined.	There are significant reductions of 2.5 percentile points for average grades and of 6% for math grades measured in secondary school for children most highly exposed to fallout in utero (ages 8–25 weeks). Impacts are strongest among those likely to have faced higher exposure levels and among children of low-income parents. No corresponding long-term health effects are found.
Bharadwaj et al. (2013); Chile; variation in ambient pollution during gestation	Fourth- and eighth-grade test outcomes are regressed on mean ambient pollutant levels in each of the 9 months of gestation and a large number of controls and fixed effects. Controls for monthly weather during gestation are included, as are mother demographic controls and community and gender fixed effects.	Math, science, and language arts test scores for ~600,000 children are linked to monthly average pollution in Santiago, Chile, during each month of gestation. Pollution and weather data are taken from the Ministry of Environment and from the NOAA summary of the day, respectively, whereas test scores and child/family data are from the Health Ministry.	A 1-SD increase in ozone levels during the third month of pregnancy led to 0.0025- and 0.00173-SD reductions in fourth-grade math and language test scores, respectively. Effects are broadly similar for eighth-grade test performance.
Black et al. (2013); Norway; temporally differentiated exposure to fallout from distant nuclear testing	Later-life outcomes (IQ, height, years of education, high school completion, and earnings at 35) are regressed on potential fallout exposure in municipality of mother's residence during weeks 8–16 of the pregnancy, as well as (*a*) a number of parental and child controls and (*b*) municipality and month of birth fixed effects. Other specifications include municipality trends, family fixed effects, and two measures of fallout.	Later-life outcomes for ~400,000 individuals in the birth cohorts of 1956–1966 are linked to measurements from 13 fallout test stations to estimate levels of monthly fallout (measured in the air and deposited) by municipality (for those within 20 km of a test station) while the individuals were in utero.	A 1-SD increase in ground exposure is associated with a 0.025-SD decrease in IQ score, ~0.15 fewer years of education, and a 0.1- to 0.25-log point reduction in earnings at age 30. Even wealthy families are unable to avoid such impacts. The largest in utero effects are found for exposures during weeks 8 to 16.

(*Continued*)

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Table 1 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Isen et al. (2013); United States; differential changes in TSPs by county due to nonattainment status	County nonattainment status is assigned on the basis of TSP levels and is then used to instrument for a large change in TSPs in counties identified as nonattainers. A D-in-D analysis compares changes in outcomes of those born in nonattainment counties versus outcomes in attainment counties before and after the 1971 CAAA implementation. Regressions are weighted by number of workers.	Earnings records for 24 states from 1998 to 2007—from the Longitudinal Employer Household Dynamics File—are merged with county and date of birth and with county-level annual average and second maximum observed TSP levels. In total, ~900,000 individuals in 888 county/year observations are included in the analysis.	A 1% increase in annual salaries of workers aged 29–31 is attributed to a 10-$\mu g/m^3$-unit decrease in TSPs during pregnancy and early childhood. Most of this effect is due to increased workforce participation. The CAAA of 1970 led to an average increase in lifetime earnings of $4,300 for the 1.5 million children born in nonattainment counties each year.
Nilsson (2009); Sweden; geographic variation in reduction of lead levels due to phaseout of leaded gasoline	OLS regressions are estimated for many outcome variables, regressing the outcome on lead exposure; on an exceedingly rich set of parent-, child-, and municipality-specific characteristics; and on fixed effects for year of birth and municipality of birth. Conditional on the municipality fixed effects, parental outcomes are not predictive of a child's lead exposure.	Ambient lead levels from moss samples from 1,000 locations in Sweden in 1975, 1980, and 1985 are aggregated to provide municipality-level estimates of lead exposure. These data are linked to socioeconomic and outcome variables for children born in the 3 years preceding each of the lead samples. Outcomes examined include high school GPA and test scores, high school completion, educational attainment, labor market earnings, and teenage motherhood. Sample sizes range from ~250,000 to ~800,000 individuals.	A significant and nonlinear relationship is shown between municipality air lead levels in early childhood and young-adult outcomes. Significant improvements in young-adult outcomes are found for the reduction in air lead levels obtained between 1972 and 1984 in Sweden, but no significant effects of further reductions are found below estimated blood lead levels of 5 $\mu g/dL$. The study also finds that low-socioeconomic-status children are affected more for any given amount of lead exposure and that this effect is not solely due to residential segregation.
Reyes (2007); United States; state-specific reduction in lead exposure due to 1970 CAAA removal of lead from gasoline	The implied first stage is supported with OLS regressions showing that gasoline lead and air lead are good predictors of child blood lead. The main specification is a state-level regression of logged per capita crime rates for the years of 1985–2002 on (*a*) effective lead exposure (estimated from gasoline lead levels of the arrested cohorts during ages 0–3), (*b*) state dummies, and (*c*) a large number of additional controls.	This study creates state/year lead exposure estimates from EPA monitor data and measures of lead per gallon of gasoline by state and year from DOE and private annual reports. Exposure estimates are linked to crime and National Health Survey data by state and year. The 918 observations for 1985–2002 include 50 states plus Washington, DC, and are weighted by population in the analysis.	A significant relationship between lead exposure in childhood and violent crime rates later in life is demonstrated, with an estimate of 0.8 for the elasticity of violent crime to childhood lead exposure. Approximately 56% of the drop in violent crime observed in the United States in the 1990s can be attributed to reductions in lead exposure during the 1970s. The effects are focused on violent crimes.

(Continued)

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Table 1 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Sanders (2012); United States; early-1980s recession and related drops in manufacturing employment	OLS and 2SLS link changes in county-level, year of birth average TSPs to changes in average performance on tenth-grade standardized tests. In 2SLS, TSP levels are instrumented by using changes in county-level manufacturing employment. School-level and year-of-birth-by-year-of-test fixed effects are included as well as controls for school-level student characteristics, county-level weather, and economic/demographic characteristics in year of birth and test. In the IV specification, county-level income is also instrumented by using national crude oil prices.	TSP measures from EPA monitors are aggregated to the county/year level for 1979–1985 and are merged with weather data from the Global Surface Summary. Employment, income, population, and density data are added from the Regional Information System, and test scores for 1994–2002 tenth-grade cohorts are provided from the Texas Education Agency. The sample size is ~100,000 students per year born in 1979–1985 at 416 schools in 30 counties.	OLS regressions suggest that a 1-SD reduction in TSPs during the year of birth is associated with a 2% of a SD increase in tenth-grade test scores. The IV estimates yield a 6% of a SD increase in test scores (and a 3% increase in county passing rates) from a 1-SD reduction in TSPs.

Abbreviations: 2SLS, two-stage least squares; CAAA, US Clean Air Act Amendment; D-in-D, difference-in-differences; DOE, Department of Energy; EPA, US Environmental Protection Agency; IV, instrumental variable; NOAA, National Oceanic and Atmospheric Administration; OLS, ordinary least squares; SD, standard deviation; TSPs, total suspended particulates.

Almond et al. (2009) study the fallout from the Chernobyl nuclear disaster by using detailed Swedish administrative data. Although Sweden is more than 500 miles away from Chernobyl, weather conditions forced some of the plume of radioactive particles to pass over Sweden. Local variation in rainfall levels led to stark geographic variation in the levels of fallout throughout the country. By comparing cohorts in affected and unaffected areas, and cohorts in utero just prior to the disaster and during the disaster, Almond et al. demonstrate that radiation exposure reduced overall grades by 2.5 percentage points and mathematics test scores by 6 percentage points, despite the fact that the amounts of radiation involved were below thresholds widely considered, at the time, to be safe. Almond et al. also find no immediate effects on health, as measured by birth outcomes and childhood hospitalizations, underscoring the latent nature of these effects.[5]

Black et al. (2013) conduct a similar analysis of the effect of in utero exposure to radiation due to fallout from nuclear tests. Using data from Norway, Black et al. first show that test frequency, proximity to the coast, and rainfall patterns influenced the deposition of fallout. They find that a one-standard-deviation increase in exposure during the eighth to sixteenth weeks of pregnancy decreased IQ scores by .025 of a standard deviation. Exposure also led to reductions in years of schooling and in adult earnings.

Using a large data set that follows Chilean children from birth, Bharadwaj et al. (2013) examine the relationship between air pollution exposure in each month of pregnancy and fourth- and eighth-grade test scores. They find significant effects of exposure to CO (and its correlates) and ozone in the third and fourth months of pregnancy, a timing that is consistent with the results found in Black et al. (2013) and Almond et al. (2009).

Nilsson (2009) investigates the long-term impact of banning leaded gasoline in Sweden during the 1970s. In an innovative design, he uses measures of lead from moss samples to infer ambient lead levels in different areas of the country and shows a wide geographic dispersion of lead across space and time. Linking the decline in ambient lead around the time of birth to later outcomes for the affected cohorts, his estimates imply that reducing lead levels from 10 to 5 μg/dL (the current regulatory standard in the United States is 15 μg/dL) increased high school graduation rates by 2.3% and earnings among young adults by 5.5%. The effects were larger for children of lower socioeconomic status.

Sanders (2012) builds on the work of Chay & Greenstone (2003b; discussed below) by asking whether cohorts affected by the reductions in US pollution caused by the recession of the early 1980s scored better on high school tests. A drawback to his analysis is that he cannot identify where the mother resided when the children were born, so he is forced to assume that children were born in the place where they attended high school. Despite this potential source of measurement error, he finds that a one-standard-deviation decrease in total suspended particles around the time of birth increases high school test scores by 6% of a standard deviation.

Isen et al. (2013) go further with a similar approach using restricted-access data on adult earnings that include information on the actual county and date of birth of each worker. Their identification strategy follows that of Chay & Greenstone (2003a) in using the pollution reductions due to the passage of the 1970 US Clean Air Act Amendments (CAAAs) a source of variation in pollution levels. Counties that were out of compliance with the new CAAA pollution thresholds were identified as noncompliant and were required to lower pollution, whereas counties with pollution levels just below the thresholds were not required to implement any

[5]The radiation levels found in Sweden are quite comparable to those emitted by radon and used in medical radiation. However, policy levers for influencing exposure from such sources are quite different from those found in typical environmental policy.

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changes. Comparing counties initially just below the threshold with those just above the threshold, Isen et al. find that each 10 $\mu g/m^3$ decrease in total suspended particles during pregnancy and early childhood resulted in a 1% increase in annual salaries. Of course, ambient levels of particulates have fallen greatly since the 1970s, so whether a similar decline in the United States today would have the same impact is not clear.

3.2. Air Pollution and Infant Health

Given the difficulty in making a direct connection between early-life exposure to pollution and later outcomes, much of the literature focuses on the effects of pollution on fetal and infant health and then relies on the growing literature linking health at birth to long-term outcomes to make inferences about the likely long-term effects. The most commonly used measures of early-childhood health are birth weight (especially low birth weight, defined as less than 2,500 g), prematurity (defined as gestation of less than 37 weeks), and either infant mortality (death within the first year of life) or neonatal mortality (death within the first month of life). **Table 2** summarizes the literature focusing on the effects of pollution on infant health. The studies in **Table 2** are organized according to whether the country is a developed country or a developing country and whether the pollutant is a criterion air pollutant or another type of pollutant.

3.2.1. Developed countries. Chay & Greenstone (2003a,b) conducted two landmark studies on the effects of air pollution. The first study (Chay & Greenstone 2003a) pioneers the research design based on the Clean Air Acts discussed above and used in subsequent studies. Applying this design to county-level data, Chay & Greenstone estimate that a one-unit decline in particulates led to 5–8 fewer infant deaths per 100,000 live births. Sanders & Stoecker (2011), using the same natural experiment, examine the effects of pollution on sex ratios at birth. Because male fetuses are thought to be more fragile than female fetuses, a decrease in the ratio of male live births to female live births is suggestive of an increase in fetal losses. Consistent with this hypothesis, Sanders & Stoecker find that a reduction in pollution increases the fraction of male fetuses. The second Chay & Greenstone study (2003b) looks at the recession of 1982, which lowered pollution in areas that experienced larger declines in manufacturing (i.e., this study follows the research design of Sanders 2012). These pollution reductions led to significant decreases in infant mortality.[6]

The levels of particulates studied by Chay & Greenstone (2003a,b) are much higher than those prevalent today; for example, US PM_{10} (particulate matter of 10 μm or less) levels fell by nearly 50% from 1980 to 2000. Moreover, the Chay & Greenstone studies are able to examine only the effects of particulates because other pollutants were not yet widely measured. In a similar inquiry, Currie & Neidell (2005) focus on a more recent time period when additional pollution measures are available. For identification, they use high-frequency variation in pollution within zip codes over time. A disadvantage of this approach is that people living in persistently more polluted or higher-variance areas may be systematically different from other people in ways that may correlate with their children's health. To control for these differences, Currie & Neidell include zip code fixed effects and zip code–specific time trends and demonstrate that decreases in CO led to improvements in infant mortality.

[6]Arguably, Chay & Greenstone were inspired by a series of epidemiological studies investigating the health effects of the opening and closing of a steel mill in Utah in the 1980s (Pope 1989, Pope et al. 1992, Ransom & Pope 1995). Other researchers have been inspired by these studies as well. For example, Parker et al. (2008) return to the same natural experiment and find that preterm births declined when the mill was closed but rebounded when it reopened.

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Table 2 Studies of air pollution, fetal health, and infant mortality

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Agarwal et al. (2010); United States; variation in chemical releases	A WLS approach regresses county-demeaned outcome variables on concentrations of toxic releases, time fixed effects, and controls for parent-level and county-level covariates.	Annual TRI data on toxic chemical releases by manufacturing site are aggregated to the county level and are merged with county-level infant fetal mortality rates in the United States for 1989 to 2002. There are more than 40,000 county/year observations, of which ~4,000 have air pollution data allowing for controls for ambient PM_{10} and ozone levels.	Reductions in annual toxic chemical releases are estimated to have led to approximately 11,694 saved infant lives over the study period, which the authors estimate (using a VSL of between $1.8 million and $8.7 million) provided a cost savings of $21 billion to $101 billion.
Arceo-Gomez et al. (2012); Mexico; week-to-week meteorological covariation with cyclical air pollution changes	Weekly levels of pollution and infant death by municipality in Mexico City are analyzed by using municipality fixed effects. Main results are IV by using the number of days of inversion layer per week to instrument for air pollution. An additional inversion is associated with a 3.5% increase in PM and with a 5.4% increase in CO.	Weekly average levels of pollution, infant and neonatal mortality, and the number of inversions from 1997 to 2006 are calculated for each of Mexico City's 56 municipalities. Pollution values are interpolated from observations at 10–26 stations (depending on availability), and inversions are identified in Ministry of Environment data.	One part per billion more CO led to .0032 more infant deaths per 100,000 births, and 1 more $\mu g/m^3$ of CO resulted in 0.24 more infant deaths per 100,000 births. PM_{10} effects are similar, although the CO impacts are larger.
Chay & Greenstone (2003a); United States; stricter regulations on nonattainment counties under the 1970 CAAAs	A difference-in-differences approach links changes in TSP levels to infant health outcomes, comparing changes in infant mortality in nonattainment counties with changes in infant mortality in other counties. The analysis also uses nonattainment status as an instrumental variable for TSP declines from 1971 to 1972, and a regression discontinuity comparison is made of counties just above and below the nonattainment threshold.	This study presents county-level data on infant health, air pollution, and other characteristics for the period from 1969 to 1974. Data come from the National Mortality and Natality Vital Statistics, the EPA, the Bureau of Economic Analysis, and the Regional Economic Information System. A panel of 501 counties is created for the analysis.	Most TSP reductions occurred in nonattainment counties. A 1% reduction in ambient average TSPs in a county led to a 0.5% fall in the infant mortality rate in the county.

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Table 2 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Chay & Greenstone (2003b); United States; 1981–1982 recession and resulting differential reductions in TSPs between counties	First differences are used to identify effects from cross-county, intrastate variation in pollution reductions due to the recession, taking into account a rich set of covariates. Counties with "large" and "medium" changes in TSPs are also compared separately with counties with "small" changes to investigate nonlinearity of health impacts from TSPs.	Data from the Census, Bureau of Economic Analysis, and National Mortality and Natality Vital Statistics are merged and aggregated to the county level. Observations are then matched with EPA monitor data that provided approximately 1,200 county-years of data for 1978–1984.	A 1% reduction in TSP levels is associated with a 0.35% reduction in infant mortality at the county level. This finding suggests that the recession led to ~2,500 fewer infant deaths nationwide during 1980–1982. Health effects are nonlinear in TSP exposure.
Coneus & Spiess (2010); Germany; cross-time and cross-location variations in pollutant levels	Mother fixed effects models with year/zip code effects as well as limited sets of covariates are estimated for a number of health outcomes for both infants and 2–3-year-olds. Cigarette use is a proxy for indoor air pollution. Models are estimated for pollution at birth, during pregnancy, and during childhood. Outcome variables include a number of physical developmental measures and illness indicators. The observation level is children per quarter.	Data from the German Socio-Economic Panel on socioeconomic conditions and health of newborns and 2–3-year-olds in the birth cohorts from 2002 to 2007 are merged with data on total-pregnancy, trimester-specific, at-birth, and first-year-of-life pollution levels from observations of the five pollutants of interest from Germany's Federal Environment Agency. Cohort sizes are ~1,100 newborns and ~700 2–3-year-olds per year.	CO has negative impacts on birth and health outcomes (especially in the third trimester). High exposure to CO led to a 289-g-lower birth weight. Marginally significant results also exist for ozone and for high levels of NO_2 and SO_2 throughout pregnancy. In utero exposure to PM_{10} does not have negative impacts. Ozone exposure at a young age and PM_{10} levels are correlated with negative health outcomes, such as a 0.70% increase in bronchitis with a one-unit increase in the 3-year average ozone level. In contrast, no clear relationships are found between early-life CO, SO_2, or NO_2 exposure and health.
Currie et al. (2011); United States; Superfund site cleanup	A difference-in-differences analysis compares changes in birth outcomes before and after Superfund site cleanup for mothers within 2 km of the site with changes in birth outcomes of mothers between 2 and 5 km of the site. Many mother and child covariates are included, and site-level or zip code fixed effects are included in some specifications. Analyses are also run on a subset of the most contaminated sites.	This study analyzes Florida, Michigan, New Jersey, Pennsylvania, and Texas births between 1989 and 2003 with mother addresses within 5 km of a Superfund site that was cleaned up. The analysis includes 154 sites, and the sample size is ~600,000 mothers, of whom ~92,000 lived within 2 km of a cleaned-up site.	Following cleanups, significant reductions (from 20% to 25%) in congenital anomalies to mothers living within 2 km of a Superfund site are observed. Also, when only a subsample of the most contaminated sites is used, significant (4.5 deaths per 1,000 live births) reductions in infant death are found across specifications; the authors note that this statistic seems too high and may be partly due to sorting.

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Table 2 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Currie & Neidell (2005); United States; intertemporal variation in pollution and infant health	Zip code pollution levels are assigned by using inverse distance weighting of monitor observations. A discrete-time hazard model is used with a linear spline in duration and pollution exposure measures for all three pollutants at 1, 2, 4, 8, 12, 20, and 32 weeks of life. Infant death is also regressed on these pollution measures as well as average measures of pollution in each trimester, gestational age, birth weight, demographic controls, and zip code/month fixed effects. OLS models, which include large numbers of covariates, are estimated for fetal death and low-birth-weight outcomes.	California EPA monitor data are used to create weekly zip code averages of ambient pollution levels that are merged with (*a*) weather data from the National Climatic Data Center and (*b*) health data on births from pregnancies that reach 26 weeks gestation from the California Birth Cohort Files for 1989–2000. In total, 4,593,001 children are in the sample. Each week of life is treated as a separate observation yielding ~250 million observations for analysis.	A one-unit reduction in CO led to 2.89 fewer deaths per 1,000 live births, resulting in ~991 fewer infant deaths in California from the reduction in CO over the 1990s. Results are robust in regional and age-specific subsamples, the omission of prenatal exposure measures, and broader temporal baskets. Authors do not find compelling evidence of prenatal exposure effects.
Currie et al. (2009b); United States; changes in pollution levels	Birth outcomes are regressed on average levels of three pollutants during the three trimesters of pregnancy, with controls for weather, mother's characteristics, and child's gender. Models with monitor-quarter fixed effects and mother fixed effects are also run. An OLS hazard model is estimated for probability of infant death in the weeks after birth with similar controls, plus birth weight classifications and a linear spline in weeks since birth. Analysis is also done separately for children with smoking mothers.	New Jersey Department of Health data from 1989 to 2003 on births and deaths for infants of mothers with addresses within 10 km of a pollution monitoring station are merged with observed pollution levels from the nearest station. There are 628,874 observations in the baseline sample, 283,393 in the mother fixed-effects sample, and 61,996 children in the smoking-mothers sample.	Negative impacts of third-trimester exposure to CO are found across specifications (with a one-unit increase in CO during the third trimester leading to an average birth weight reduction of 16.65 g). Results are inconsistent and less significant for PM_{10} and ozone. The negative effects of CO exposure continue after birth in the infant sample, with a 1-ppm decline in average CO levels in the first 2 weeks after birth, leading to 0.18 fewer deaths per 1,000 live births. The negative impacts of CO are found even at low levels of ambient CO.

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Table 2 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Currie & Schmieder (2009); United States; interyear, within-county variation of toxin releases	Effects of toxic chemical air releases (weighted by county area) are assessed on birth weights, gestational ages, and infant mortality. Individual regressions are run for each outcome variable against all toxic releases, chemicals identified as affecting development, chemicals identified as not affecting development, VOCs, heavy metals, and some individual toxins. A broad set of county-level controls are used along with county and year fixed effects. Similar analyses compare fugitive with stack toxic emissions.	Approximately 5,200 county/year observations are created with birth and infant health data for births in the first 3 months of the year from the National Mortality and Natality Vital Statistics data. These data are merged with the prior year's TRI data and with a rich set of county-level demographic and socioeconomic controls. The California Office of Environmental Health Hazard Assessment's list of known developmental toxicants is used to identify toxicants of interest.	Significant, but small-magnitude, negative effects are found for releases of a number of toxins on gestation, birth weights, and probability of infant death. Reductions in the emissions of toluene, lead, and cadmium account for ~4% of the reduction in infant mortality that occurred in the late 1980s and 1990s. Fugitive emissions have larger effects. Results are much stronger for toxics thought to have developmental effects.
Currie & Walker (2011); United States; introduction of congestion-reducing automated toll payment systems	A difference-in-differences approach compares changes in birth outcomes (low birth weight and prematurity) for mothers living within 2 km of a converted toll plaza with changes in birth outcomes of mothers living between 2 and 10 km of a toll station and within 3 km of a major freeway. Similar pretrends are demonstrated between treatment and control groups. Regressions control for mother's race, age, and education level; for multiple births; and for child's gender. Plaza, year, and month fixed effects are also included.	Location and date of the opening of E-ZPass toll plaza conversions are linked to National Mortality and Natality Vital Statistics records for mothers living near toll plazas in New Jersey and Pennsylvania for the years of 1994–2003 and 1997–2002, respectively. The sample consists of mothers living within 10 km of 98 toll plazas, yielding ~30,000 birth observations before and after conversion in the treatment group and >150,000 observations before and after conversion in the control group.	Significant reductions in prematurity of 8.6% and in low-birth-weight births of 9.3% are associated with the conversion of toll plazas to the EZ-Pass systems. The authors show no significant differential shift in housing prices near converted toll stations, suggesting that sorting is not occurring in the short term. Results are robust for nonsmokers, defining smaller treatment and control areas and the use of mother fixed effects. Effects are much stronger among African-American mothers.

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Table 2 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Foster et al. (2009); Mexico; certification of businesses under Mexico's clean industry certificate program	Estimated air quality and infant health outcomes are separately regressed onto a variable that captures the fraction of firms within a municipality that have been certified by a given month. Municipality and month/year fixed effects and both time-varying municipality controls and the square of a number of time-invariant municipality characteristics are also included. Only 94 auditors can grant certification, and distance to these auditors is used as an instrument for certification.	Daily air quality estimates for all of Mexico are created from aerosol optical depth (AOD) measurements in MODIS satellite data. AOD estimates are aggregated to the monthly/municipality level and are merged with estimated temperature and dew-point controls, infant mortality data, firm and employment data, and clean industry certification awards. The analysis focuses on 1,706 municipalities from 2000 to 2006, yielding ~32,000 observations.	The authors estimate that certification of all firms in a municipality would lead to a 3.6% improvement in AOD and to a 16% reduction in respiratory-related infant mortality. These results are combined to suggest that a 1% increase in AOD leads to a 4.4% increase in infant mortality due to respiratory ailments.
Greenstone & Hanna (2011); India; implementation of pollution control policies	Pollutant levels (and later infant mortality rates) are regressed on a vector of dummies for years when each policy was in force, on city and year fixed effects, and on consumption and literacy controls. Three additional specifications are run to test for whether yearly average pollution levels (estimated in the first specification) are affected by policy implementations.	Air pollution data for 1987–2007 for 140 cities and river water monitor data for 1986–2005 for 162 rivers from India's Central Pollution Control Board are merged with a city/year data set on pollution regulations and with city/year infant mortality and socioeconomic data.	Air pollution regulations reduced average ambient levels of particulates (by 19%), of SO_2 (by 69%), and of NO_2 (by an insignificant 15%) but led to statistically insignificant improvements in infant mortality. The water pollution regulations investigated showed no statistically significant effects on pollution or on health.
Janke et al. (2009); United Kingdom; intertemporal pollutant level variation	Various mortality rates are regressed on annual levels of the four pollutants, on a moderate number of time-varying local authority covariates, on a time trend, on region-specific time trends, and on a local authority fixed effect.	Pollution monitor data for 1998–2005 from a number of sources are aggregated to annual averages at the local-authority level and then linked to mortality data at the authority/year level over the same period. The analysis uses ~2,300 authority/year observations.	A 10-$\mu g/m^3$ increase in PM_{10} is associated with an increase in death rate of 4 per 100,000 births among those under age 15 (from a mean mortality rate of 44 per 100,000 births). Other pollutants are not found to have significant impacts on child mortality.

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Table 2 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Jayachandran (2009); Indonesia; 1997 wildfires on the islands of Sumatra and Kalimantan	Regressions of the natural log of district/month cohort sizes on measures of smoke at (the month of), before (the 3 months prior to), and after (the 3 months subsequent to) birth as well as on birth month/year and subdistrict fixed effects. Dates of analysis were chosen to avoid fertility effects the fires might have had.	Indonesian census data from 2000, with analysis by birth-month cohorts for December 1996 to May 1998 for 3,751 Indonesian subdistricts. There are ~67,000 children in these ~700 cohorts. The median monthly levels of daily air pollution are proxied by aerosol measures from the Earth Probe Total Ozone Mapping Spectrometer mapped onto subdistricts.	Pollution from fires led to a 1.2% decrease in cohort size among children in the third trimester of pregnancy during the 5-month period of the fires. This finding implies that 15,600 fetal, infant, and child deaths are attributable to the fires, a 20% overall increase in mortality of those under 3 years old. Results are more pronounced among boys and among lower-income households.
Knittel et al. (2011); United States; weekly variation in ambient pollution (instrumented) and infant mortality	Three pollutants of interest are instrumented by using traffic congestion interacted with weather conditions. The main specification is a discrete-time hazard model estimated as a linear probability model by using person/week observations with controls for age in weeks with a flexible spline. Analysis is done separately for the 1989–2000 and 2002–2007 periods to assess whether lower pollution levels have different health effects.	Ambient air pollutant levels, weather conditions, and traffic densities for 1989–2000 and for 2002–2007 are merged and aggregated to the zip code/week level for much of Central and Southern California. Infants are assigned to a zip code and are tracked weekly through the first 52 weeks of life, yielding a sample of ~150 million infant/weeks during the early time period and ~75 million observations in the later period.	Strong links between traffic congestion and pollution are demonstrated. A one-unit reduction in PM_{10} led to 18 fewer infant deaths per 100,000 live births. There is little evidence of stable impacts from CO or from ozone.
Lüchinger (2010); Germany; mandated installation of SO_2 scrubbers on power plants	A difference-in-differences comparison of the treatment—installation of a sulfur scrubber on a power plant—is made across treatment and control groups made up of counties that are downwind and upwind of power plants. The frequency of days downwind from a plant in a given year is used to weight the treatment group. In addition to wind direction, treatment levels for a county are determined by scrubber installation, plant size, and plant distance to each county.	Infant mortality data for 1985–2003 are linked to annual monitor-level mean SO_2 levels and are aggregated to the county level. Power plant characteristics and scrubber installation data are available for all 303 fossil fuel plants, which have a >100-MW capacity during the time period of interest, and monitor-collected wind data are linked to each plant. The main analysis uses ~7,500 county/year observations.	Instrumenting for pollution leads to higher estimates of the effects of SO_2 on infant mortality than does OLS. The author finds an elasticity of 0.08–0.13, which suggests that the reduction in SO_2 observed over the study period led to 895–1,528 fewer infant deaths annually in Germany over that same period. One-third of the infant mortality effects of higher SO_2 exposure are realized in the first day after birth, and 50–80% of the effects are realized during the first month outside of the womb.

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Table 2 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Sanders & Stoecker (2011); United States; 1970 CAAAs	Regression discontinuity at the time of CAAA implementation occurs via a county-level, first-differences model with state fixed effects, which is estimated with the change in pollution from 1970 to 1972 instrumented by county estimated nonattainment status. The outcome examined is the ratio of male to female live births; male fetuses are more susceptible to in utero insults. Thus, increased shares of male live births suggest fewer fetal deaths. A large number of county-level covariates, including TSP level in 1970, are included as controls.	Birth data from the National Natality Vital Statistics microdata are merged with EPA measures of ambient TSPs and are aggregated to the county/year level. This analysis yields 281 counties with full desired data, representing 50% of live births. First differences are calculated on changes from 1970 to 1972.	Children are more sensitive to exposure to TSPs in utero than after birth. Overall, a one-unit increase in annual average TSP ambient pollution is estimated to lead to a 0.088-percentage-point change in the probability of a birth being male. This finding suggests that the CAAAs led to a 3.1% change in probability of a male birth and to an estimated 21,000 to 134,000 avoided fetal deaths in affected counties (which is 2% to 13% of total births).
Sneeringer (2009); United States; spatial variation in livestock operations due to farm consolidations	Unit counts of livestock proxy for pollution from livestock farming. An OLS regression is run for health outcomes on the number of livestock in a county and on a large number of time-varying county covariates that capture demographics, population and housing characteristics, weather controls, industrial concentrations, Clean Water Act permits, and other attributes. Year, county, and state fixed effects are also included in the model.	Livestock-by-county information is taken from a proprietary source based on Census of Agriculture data from the 1982, 1987, 1992, and 1997 agricultural censuses and is merged with restricted-use birth and death records from the National Center for Health Statistics for 1980–1999. Additional county-level controls are taken from a variety of other sources. Ultimately, 9,223 county/5-year-period observations are used on the basis of ~75 million total births.	An increase of 100,000 animal units in a county resulted in 123 more deaths of infants <1 year old and in 100 more deaths of infants <28 days old per 100,000 live births. The average annual unit increase from 1982 to 1997 (for counties with increases) was 35%, suggesting a 2.8% increase in infant mortality in these counties and a total of 3,500 additional infant deaths in the United States over the time period. Effects are connected to air pollution rather than to water pollution through a number of findings.

Abbreviations: CAAA, US Clean Air Act Amendment; EPA, US Environmental Protection Agency [California EPA, California Environmental Protection Agency]; IV, instrumental variable; MODIS, Moderate Resolution Imaging Spectroradiometer; OLS, ordinary least squares; PM, particulate matter; PM_{10}, particulate matter of 10 μm or less; ppm, part(s) per million; TRI, Toxic Release Inventory; TSP, total suspended particulate; VOCs, volatile organic compounds; VSL, value of a statistical life; WLS, weighted least squares.

In a related study, Currie et al. (2009b) use a large sample of infants born in New Jersey from 1989 to 2006 and who were subjected to different levels of pollution in utero. Currie et al. control for fixed elements of family background shared by siblings by including family fixed effects. They also focus on a sample of mothers who lived near pollution monitors to improve their assignment of pollution exposure. They find that babies exposed in utero to higher levels of CO suffered reduced birth weight and gestation length relative to their siblings, even though ambient CO levels were generally lower than those mandated by current US Environmental Protection Agency (EPA) standards. Their estimates imply that, on average, moving from a high-CO area to a low-CO area would have a larger effect on infant health than having a pregnant woman reduce her smoking from ten cigarettes a day to zero.

Because many papers find negative health effects of CO, and CO comes mostly from cars, Currie & Walker (2011) exploit the introduction of electronic toll collection devices (E-ZPass) in New Jersey and Pennsylvania to directly examine the effect of automobile exhaust on infant health. Much of the pollution produced by automobiles occurs during idling and acceleration, so the introduction of E-ZPass greatly reduced auto emissions near toll plazas. For example, E-ZPass reduced CO by approximately 40% in the vicinity of toll plazas. Comparing mothers near toll plazas (<2 km) with those who lived along the same busy roadways but further away from toll plazas (2–10 km), Currie & Walker find that E-ZPass reduced the incidence of low birth weight and prematurity by approximately 10%. In a related paper, Knittel et al. (2011) examine the effect of traffic congestion in California by using data on traffic jams that temporarily increased pollution levels. They also find significant effects of even relatively low levels of pollution on infant mortality rates.

Recently, the number of studies conducted outside of the United States has grown considerably. Using a design similar to that of Currie & Neidell (2005), Coneus & Spiess (2010) find large effects of CO on infant health in Germany. Lüchinger (2010), also focusing on Germany, uses the mandating of sulfur dioxide (SO_2) scrubbers in power plants as a natural experiment. He finds that reductions in SO_2 led to significant decreases in the rate of infant mortality. Janke et al. (2009) examine the relationship between localized pollution levels in Great Britain between 1998 and 2005 and the deaths of children under 15.[7] They estimate that a reduction of 10 $\mu g/m^3$ in PM_{10} is associated with 4 fewer deaths per 100,000 births.

3.2.2. Developing countries. The impacts of pollution in developing countries are of independent interest because pollution levels are generally higher and infant health is often much worse there than in more developed countries. Thus, the same health insults may have larger effects, and the data may also be used to test for potential nonlinear effects of pollution. However, whereas data on pollution and health are often reliably recorded in more developed nations, such data may be more difficult to obtain in less developed countries. Jayachandran (2009) overcomes this obstacle by using satellite aerosol measures to track smoke from fires in Indonesia in 1997 and by using data on missing children to infer infant mortality. She finds a reduction in cohort size for those exposed to the fires' smoke during the third trimester of pregnancy and calculates that the fires resulted in a 20% increase in deaths among fetuses and children less than 3 years of age.

Foster et al. (2009) also use satellite measurements to approximate pollution levels throughout Mexico. Using participation in a voluntary pollution reduction program as an instrumental variable, Foster et al. show that reductions in pollution improve infant mortality from respiratory causes. Also focused on Mexico, Arceo-Gomez et al. (2012) use thermal inversions, which trap

[7]We include this study in **Table 2** because the vast majority of such deaths are those of infants under 1 year of age.

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pollution, as an instrumental variable and find that CO has stronger per-unit effects on infant mortality than in the United States.

Cesur et al. (2013) examine the switch from coal to natural gas in Turkey and find that a one-percentage-point increase in subscriptions to natural gas was associated with a 4% decline in infant mortality. A notable feature of this study is that, instead of focusing on the effect of a pollutant per se, it focuses on a change in fuel delivery, which is perhaps more relevant from a policy perspective. Greenstone & Hanna (2011) use air pollution data from 140 Indian cities and find that air pollution regulation substantially reduced pollution. These regulations also led to a statistically insignificant decrease in infant mortality, although the several data limitations noted suggest that their results should be interpreted with caution.

3.2.3. Noncriteria pollutants. Most of the studies in **Table 2** focus on so-called criteria pollutants, including ozone, particulate matter, CO, nitrogen oxides, SO_2, and lead, all of which are regulated under the US Clean Air Acts. Much less is known about other hazardous pollutants. Industrial plants in the United States emit approximately four billion pounds of toxic pollutants annually, including more than 80,000 different chemical compounds (GAO 2009). Regulation of these toxins is in its infancy, and most toxins have not undergone any form of toxicity testing (CDC 2009). For example, it has been known for decades that mercury is highly toxic, yet the first regulation of mercury compounds in the United States—the Mercury and Air Toxics Standards—was unveiled in December 2011.

Two studies use US county-level data from the EPA's Toxic Release Inventory to document a correlation between higher emissions and infant death (Currie & Schmieder 2009, Agarwal et al. 2010). Currie et al. (2013) further examine the effects of toxic emissions by using openings and closures of more than 1,600 industrial plants that reported toxic emissions. By matching 1989–2003 data on 11 million individual birth records from five large states (Florida, Michigan, New Jersey, Pennsylvania, and Texas) with pollution monitor data, Currie et al. first show that toxics can be detected up to a mile away from a plant and that the average mother in these states lived within a mile of these plants. They then show that infants within a mile of a plant have a 2%-higher incidence of low birth weight compared with infants one to two miles away, despite the fact that the two groups share equally in the economic benefits of plant operation. Although housing values were also reduced, such reductions occurred only within a half-mile of a plant, suggesting that some people at risk of poor health outcomes are unaware of the hazards.

Another paper that moves beyond the consideration of criterion air pollutants is Sneeringer (2009), which examines pollution due to large-scale livestock operations. Although these operations have generated concerns regarding the pollution of water sources, animal wastes are also associated with the production of particulate matter and of the noncriteria pollutants hydrogen sulfide gas and ammonia, all of which can be harmful to the developing fetus. Sneeringer finds that a doubling of livestock production in a county is associated with a 7.4% increase in infant mortality. Although she cannot demonstrate a first-stage effect of the operations on pollution, some evidence that the effect is primarily due to air pollution is obtained by examining causes of death (accidents and homicide versus respiratory causes) and by comparing counties with differing dependence on well water (higher dependence on well water is subject to more contamination).

3.3. Air Pollution and the Well-Being of Older Children

Table 3 summarizes studies examining the effects of pollution on the health of older children. Because there is no convenient summary measure of child health that is analogous to birth weight for infant health, most studies of child health focus on hospitalizations for respiratory infections or

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Table 3 Studies of air pollution and child health

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Beatty & Shimshack (2011); United States; school bus emissions reductions	A two-period D-in-D specification is used whereby changes in health outcomes in districts that had significantly retrofitted their bus fleets are compared with changes in health outcomes in districts that had not yet begun retrofits. The second specification is a month-by-month D-in-D (with month, year, and district dummies) comparing before and after retrofit periods. All specifications control for a small number of district and weather covariates and county and state/year fixed effects.	Washington State data on a (state-funded) bus retrofit program from 53 school districts (with ~4,000 total buses) are linked to hospital discharge data for 1996–2006 and with census demographic data. Data are aggregated to the school district/month level, with a total of ~5,830 observations for analysis.	The preferred estimates demonstrate that school districts that adopt emissions-reducing retrofits on their school bus fleets experience 23% fewer bronchitis and asthma cases and 37% fewer children's pneumonia cases per month. Results are attributed to within-bus exposure to bus emissions.
Lavaine & Neidell (2013); France; temporary shutdown (due to strikes) of oil refineries	Pollution exposure of admitted patients is estimated. Then census-tract respiratory hospital admissions are regressed on this exposure measure; on weather controls; and on tract, month, and year fixed effects. As exposure is endogenous, it is instrumented with an indicator for proximity to a refining facility affected by strikes and whether the month is October 2010 (when the strikes were in force).	Respiratory hospitalization data from the French National Hospital Discharge Database are merged with pollution, weather, and socioeconomic data. After the authors drop tracts and refineries for which key pieces of data are missing, 3,100 French census tracts are left with data for 2007–2010.	Authors find that SO_2 levels well below current quality standards led to significant health impacts, especially among the at-risk populations of the elderly and the young. A 1-$\mu g/m^3$ decrease in SO_2 concentrations for 1 month led to a 5-g increase in average birth weights and to a 0.18-day increase in gestational age. Impacts appear to be strongest during the third trimester.
Lleras-Muney (2010); United States; exogenous relocation of the families of Army personnel	Exogenous location assignments of army personnel are used to identify contemporaneous effects of five pollutants on child hospitalizations. The probability a child was hospitalized in a given year is regressed on levels of the five pollutants, weather controls, child characteristics, base fixed effects, base/year characteristics, and father's rank/occupation/year fixed effects.	Annual individual-level data on all enlisted men stationed in the continental United States from 1988 to 1998, and hospitalization data (including condition) for all the men's wives and children, are linked (via kriging methods) to annual EPA and weather data. These data provide 159,275 annual observations of children 0–5 years old and 44,663 annual observations of children under age 1.	No impacts are found for children 0–1 year old. For children 2–5 years old, probabilities of respiratory hospitalization are increased by higher levels of ozone in all samples, and CO also contributes significantly for children of families that did not move in a given year. A 1-SD increase in ozone led to an 8–25% increase in the likelihood of respiratory hospitalization for children 2–5 years old, implying an elasticity of 0.5 to 1.5.

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Table 3 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Neidell (2009); United States; smog alerts	Behavior change in response to ozone alerts is assessed with a regression discontinuity analysis of attendance at outdoor attractions regressed on an indicator for a local ozone alert; forecast ozone levels; weather and other air pollutant controls; and indicators for holidays, summer schedule, and day of week. Analyses also examine the effect of alerts on asthma hospitalizations.	Daily attendance data for two outdoor attractions (the Los Angeles Zoo and Griffith Observatory) for 1989–1997 are merged with hospital discharge data, weather data, and data on both predicted and actual ozone levels in ten air monitoring zones in the Los Angeles area.	People respond to public information about pollution by spending less time outside. Ignoring avoidance behavior understates the negative impacts of ozone on health outcomes of the young and elderly. A 0.01-ppm increase in 5-day ozone levels increases child hospital admissions by 1.09%, but controlling for smog alerts increases this number to 2.88%.
Neidell (2004); United States; intra–zip code variation in seasonal air pollution levels	Zip code/month emergency room admissions for asthma are regressed on contemporaneous levels of four air pollutants, on a number of controls, and on dummy variables for each zip code/year and year/month. The model is estimated separately for each of five age groups ages 1–18.	Zip code–level data for California are aggregated for hospital discharges due to asthma for ages 1–18, for weather monitors, and for air pollution monitors for 1992–1998. Demographic, home values, and ozone alert data are also used. This provides ~50,000 zip code/month observations for analysis.	CO has a significant effect on asthma for children ages 1–18. If 1998 levels of CO had been at their 1992 levels, 5–14% more hospital admissions due to asthma would have been expected. Avoidance behavior significantly reduces the negative effects of air pollution. Negative air pollution effects are larger among children of lower socioeconomic status.
Ransom & Pope (1995); United States; temporary closure of a steel mill in Utah	A D-in-D approach comparing logged health outcomes in a valley with a (intermittently shut down) steel mill with health outcomes in a nearby valley (with no mill) is used with negative binomial regression models. Regressions include seasonal controls but few other covariates.	Data on local counts of daily deaths and hospital admissions (including reason for admission) for individuals living in two distinct valleys in Utah (the Utah and Cache Valleys) are linked to data on the temporary 13-month closure of a large steel mill (due to a labor dispute) in 1986 and 1987.	Respiratory hospital admissions increased significantly when the mill was open (relative to the control). Admissions due to bronchitis and asthma doubled for preschoolers in the treatment valley when the mill was open versus closed (almost no change occurred in the control valley) and resulted in ~60 additional hospital admissions per year in this age group.

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Table 3 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Reyes (2012); United States; differential rates of declines in leaded fuel usage between states	The relationship between blood lead and effective grams of lead in purchased gasoline is determined via a simple OLS regression using the NHANES II data, and the resulting estimates are used to predict (by state, age, year of birth, and a number of other individual characteristics) blood lead levels at ages 0–3 for those surveyed in the NLSY. Childhood and young-adult outcomes are then regressed on this estimated value of blood lead and on a vector of individual demographics, as well as on dummies for mother's age and birth cohorts.	Individual outcome data on ~10,000 young adults from the NLSY 79 and NLSY 97 surveys are linked to state/month estimates of effective grams of lead per gallon of purchased gasoline (for the time period when the child was 0–3 years of age) and to census data. Additionally, 1976–1980 blood-level data from 2,322 children under age 6 from the NHANES II are linked to the grams of lead per gallon measure by state.	The large negative impacts of early-childhood lead exposure include childhood behavioral problems, teenage aggression and pregnancy, and young-adult criminal behaviors. The elasticities between these behaviors and lead exposure range from 0.2 to 1.0.
Schlenker & Walker (2011); United States; airport delays at East Coast hubs	This study examines the effect of pollution from airports on emergency room visits and on hospitalizations for respiratory and heart ailments. The study instruments for pollution levels in zip codes near airports with delays at East Coast hub airports (such delays led to delays and increased taxiing and thus to increased pollution at the California airports that are the focus of this study). Additionally, wind variation (interacted with East Coast taxiing congestion) is used as an additional instrument for pollution in zip codes near major California airports.	Daily data on air pollution levels, weather, hospital admissions, and emergency room visits for zip codes surrounding California's 12 largest airports are linked to Department of Transportation data on taxiing time at these airports and three major eastern hubs. Zip code direction from the nearest airport and wind direction data are also included. The main sample is ~180,000 day/zip code observations from 2005 to 2007.	Increased taxiing led to significant increases in ground-level air pollution near airports. A 1-SD increase in taxiing time at LAX increased CO levels near the airport by ~0.32 SD 10 km from the airport. A 1-ppb increase in CO led to 0.8 additional daily hospital visits per 10 million children under the age of 5 years due to asthma and led to 5.5 additional hospital visits due to all respiratory ailments. The elderly and the young tend to be more sensitive, but impacts of CO are found across all ages. Significant effects are not found for NO_2 or for ozone.

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Table 3 *(Continued)*

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Yu (2011); China; intervention assignment	A number of D-in-D models are estimated. Due to apparent nonrandom sample selection, assigned treatment and control groups are not the preferred specification. The author employs propensity score matching following to better construct matched treatment and control groups. The matching variables are validated and checked by using false treatments.	A total of 1,050 children <5 years of age in rural Chinese households were examined six times before and eight times after the intervention, which was implemented in three groups of households. The first group received subsidized stoves and a behavioral intervention, the second received only a behavioral intervention, and the third was a control.	Both interventions were effective in reducing the acute incidence of both upper respiratory infections (by 9–23%) and lower respiratory infections (by 1–3%) among small children, although the additional intervention of stove subsidization is not found to have significantly better outcomes among children.

Abbreviations: D-in-D, difference-in-differences; EPA, US Environmental Protection Agency; NHANES, National Health and Nutrition Examination Survey; NLSY, National Longitudinal Survey of Youth; OLS, ordinary least squares; ppb, part(s) per billion; ppm, part(s) per million; SD, standard deviation.

asthma. Respiratory ailments are a leading cause of hospitalizations among children, comparable in incidence only to the incidence of injuries, which are unlikely to be influenced by pollution.[8]

Ransom & Pope (1995) produce one of the first quasi-experimental studies of this type, using the closure of a local steel mill as a natural experiment. They find that child hospitalizations for respiratory conditions fell when the mill was closed and rebounded when the mill reopened. Since then, a number of studies have used other clever natural experiments to identify the effects of pollution. Beatty & Shimshack (2011) look at mandatory reductions in school bus emissions, Lleras-Muney (2010) examines children in military households who are exogenously assigned to areas with different pollution levels on the basis of the military's needs, Lavaine & Neidell (2013) use strikes that shut down oil refineries in France, Yu (2011) studies a behavior modification experiment designed to reduce indoor air pollution from stoves, and Schlenker & Walker (2011) use changes in pollution at California airports due to delays at East Coast hubs. All these papers find that reductions in pollution significantly reduced child respiratory problems.

Two papers in **Table 3** (Neidell 2004, 2009) highlight the potential impact of avoidance behavior on the estimated effects of pollution. People take actions ranging from changes in daily activities to moving their residence to reduce exposures to harmful pollutants. If people act to lessen their exposure, then the potentially harmful effects of pollution may be understated by estimation procedures that do not take these actions into account. A growing body of evidence suggests that changes in daily actions effectively reduce exposure to pollution, even when those actions are not taken directly in response to poor air quality. Consistent with the framework above, the Neidell (2004, 2009) papers suggest that the effects of pollution exposure are much greater than are generally estimated when precautionary actions are ignored.[9]

Table 4 illustrates that there are many fewer studies of the effects of pollution on nonhealth child outcomes such as schooling attainment and test scores. This reality reflects both limitations on the available data and conceptual difficulties in elucidating the way that pollution can be expected to affect test scores. For example, because test scores reflect cumulative knowledge, how should we account for the effects of cumulative exposure to pollution? In principle, the same issue applies to long-run health outcomes. However, as discussed above, most of the research examining the effects of pollution on health outcomes focuses on relatively short run effects (e.g., effects of in utero pollution on birth weight or effects of pollution on hospitalizations for asthma).

One potential mechanism underlying an effect of pollution on test scores is through absence—children's frequent absences from school because of high pollution levels may interfere with their ability to learn. Currie et al. (2009a) find some evidence that, in Texas, higher pollution levels over 6-week attendance periods are associated with more student absences. Zweig et al. (2009) extend this analysis by using class-level performance data at the school-year level to show that higher pollution levels decrease scores on annual achievement tests. To address concerns that differences in the student populations might be correlated with both pollution and lower test scores, Zweig et al. include school fixed effects as well as observable student and family characteristics in their analysis. Reyes (2011) does not have panel data but shows a strong cross-sectional link between test scores in elementary schools in the 2000s and childhood lead levels in the same areas of the schools a decade earlier. Lavy et al. (2012) examine whether high pollution on the day of

[8]As such, injuries can be a useful control condition for studies examining hospitalizations.

[9]Avoidance behavior is of considerable interest in its own right because it constitutes an important cost of pollution. Indeed, a sizable literature focuses on estimating avoidance behavior to derive more complete measures of willingness to pay to avoid pollution (e.g., Harrington & Portney 1987, Agee & Crocker 1994, Mansfield et al. 2006, Deschênes et al. 2012, Gerking et al. 2012). A review of this literature is beyond the scope of the current survey.

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Table 4 Studies of air pollution and children's schooling and cognition

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Currie et al. (2009a); United States; changes in counts of binned pollution levels	A triple-differences model is employed, holding school, year, and 6-week attendance period characteristics constant to examine the effects of shifts in the number of days in five levels bins on attendance for each of the four pollutants of interest. School demographic and age characteristics, precipitation, and temperature are controlled for.	Administrative data from 1996 to 2001 from schools within ten miles of a pollution monitor in the 39 largest school districts in Texas are merged with pollution data from these monitors. Attendance data from the 1,512 schools in 6-week blocks are at the school level, so hourly pollution data are aggregated, resulting in >12 million student attendance period/year observations.	CO levels below the current EPA standards led to increases in school absences. The reduction in high-CO days during the period of the study led to a 0.8-percentage-point (on a 3.58% base) reduction in absences, with large impacts for vulnerable populations such as asthmatics. No statistically significant relationship is found between more days with high PM_{10} or ozone and increased absences.
Lavy et al. (2012); Israel; natural variation in pollution on test days	Fixed-effects regressions are run of student test scores on contemporaneous weather and pollution variables, with results presented for student, school, and city level fixed-effects models. Controls for student and parental characteristics and month- and test-level fixed effects are also included.	Approximately 300,000 scores (for $PM_{2.5}$) and approximately 150,000 scores (for other pollutants) from the Bagrut test—a high school graduation requirement for academic tracking—from 2000 to 2002 are matched to contemporaneous pollution (from 139 monitors) and to weather conditions on the basis of city of test.	Higher levels of both $PM_{2.5}$ and CO are associated with lower scores. A $PM_{2.5}$ Air Quality Index (AQI) of >100 is associated with ~2.5 fewer points (out of 100) and a CO AQI of >100 is associated with ~9.5 fewer points. This effect is homogeneous for CO but is more intense among groups with higher rates of asthma for $PM_{2.5}$.
Reyes (2011); United States; identification from within-school, intertemporal variation in blood lead levels	Cohort average test scores are regressed on a measure of blood lead (either levels or indicator of the number of children over certain thresholds); on a broad set of community-, district-, and school-specific controls; and on year fixed effects. An OLS regression weighted by cohort size is the main estimation method.	A panel of school-level cohort/year data on third and fourth graders from >1,000 public schools in Massachusetts between 2000 and 2009 is created through the aggregation of individual standardized test scores and blood-level measurements. Additional school- and community-level controls are gathered from state and federal data sources. The analysis uses ~18,000 cohort/year observations.	Blood lead levels from the 1990s coupled with test performance in the 2000s demonstrates the strong cross-sectional link between childhood blood lead levels and later test scores. Such links are not robust to the inclusion of significant covariates. The lead reduction levels observed over the time period reduced the share of children scoring unsatisfactorily on standardized tests by 1–2 percentage points.

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Table 4 (*Continued*)

Paper; country; source of variation	Methods	Data and sample size	Outcomes
Zweig et al. (2009); United States; identification from intertemporal variation of pollution and test scores within cities	Average class test scores by subject are regressed on a number of measures of contemporaneous pollution, controlling for time-variant average student, family, and school characteristics; city unemployment levels; and school fixed effects. A specification with year fixed effects is also estimated.	Individual survey data from three cohorts of students from the Children's Health Study (CHS) in 88 Southern Californian schools are aggregated to the class-and school-year level and are merged with publicly available data on schools, communities, and test scores. These 216 observations are linked to contemporaneous, yearly average measures of air pollution for monitors placed by the CHS.	A 10% decrease in the ambient levels of PM_{10}, $PM_{2.5}$, and NO_2 led to increases in scores on standardized math tests of 0.15%, 0.34%, and 0.18%, respectively. Only $PM_{2.5}$ levels are found to contribute significantly to reading scores, with a 10% reduction in the annual average $PM_{2.5}$ level associated with a 0.21% increase in reading scores. Annual ozone levels are not found to contribute significantly to reading or math scores.

Abbreviations: OLS, ordinary least squares; $PM_{2.5}$, particulate matter of 2.5 μm or less; PM_{10}, particulate matter of 10 μm or less.

a high-stakes test affects student performance. Using multiple test results for the same student and student fixed effects, Lavy et al. show that Israeli students earned lower scores when subjected to higher pollution on the day of the test.

4. CONCLUSIONS

The research reviewed in this survey is motivated by two broader literatures spanning several academic fields. The first literature suggests that events in early life have effects that reach into adulthood. The second demonstrates that pollution, especially discrete episodes of intense pollution such as the London Fog of 1952, has significant effects on health. Putting these observations together led researchers to probe this relationship directly: Does early-life exposure to pollution have long-term consequences later in life? The studies reviewed here provide strong evidence that such exposure can. Like all good social science research, this realization leads to a further set of questions.

First, can we identify threshold levels of particular chemicals that are safe for fetuses and young children? There is a preponderance of evidence that high levels of pollution (either historically in developed countries or currently in developing countries) are harmful. A particularly important question for policy is whether there is a safe level of these substances. A more subtle issue is that the thresholds may differ across groups. For example, children in developing countries may react more negatively to a given dose of pollution if they are already weakened due to other health shocks. Conversely, in an environment in which the selective pressures of a hostile environment imply that only the strongest survive, a given dose of pollution may have milder effects.

Second, can we identify factors that protect against or exacerbate the effects of exposure? As we stress above, the extent to which parents can avoid exposure has important implications for the interpretation of the estimated effects of pollution. Whether parents can affect long-run outcomes by remediating or exacerbating these early effects is similarly important.

Third, can we provide more evidence about how early-life exposure to pollutants affects not only health but also other important economic outcomes such as education, labor force participation, and earnings? Our survey of the literature suggests that relatively little has been done in this regard, particularly studies that directly examine the long-run impacts of pollution exposure in early life. Quantifying effects on these outcomes is important for policy analysis.

Given the potentially long-lasting consequences from early exposure to pollution, the marginal returns to pollution control may be particularly high for this vulnerable segment of the population. As economists extend their reach into this arena and shed light on these key questions, their analysis will better inform policy makers who must make significant decisions regarding the different approaches to pollution control. Together, these questions compose an exciting and important research agenda.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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