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TOXIFIED TO THE BONE:
EARLY-LIFE AND CHILDHOOD EXPOSURE TO LEAD AND MEN'S OLD-AGE MORTALITY

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ABSTRACT

Several research strands document the life-cycle impacts of lead exposure during early life. Yet little is known about the long-run effects of lead exposure during early life on old-age mortality outcomes. In this study, we employ Social Security Administration death records linked to the full-count 1940 census and document that birth-city lead status negatively affects later life old age longevity. These impacts are larger for cities with acidic water and older pipeline systems that allow higher lead levels to leach into drinking water. Further, we show that the impacts are almost exclusively concentrated on the lead status of the birth-city and not the city of residence later in life. An instrumental variable strategy suggests reductions in longevity associated with birth-city lead status of about 9.6 months. We also find education, socioeconomic standing, and income reductions during early adulthood as candidate mechanisms. Finally, we use WWII enlistment data and observe reductions in measures of cognitive ability among lead-exposed individuals.

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1. Introduction

Following the late 19th century industrial revolution, there was a sharp rise in products that employed lead as their constituents. For instance, farm management specialists started using lead arsenate at unprecedented levels during the first decades of the 20th century. During the same period, many cities installed city-wide pipe water systems, many of which employed lead as their primary product or a combination of lead and other materials such as iron. Although the negative health impacts of lead were known to public health specialists and critics regularly argued against using lead specifically in the water system, lack of universal consensus and low levels of regulation and monitoring resulted in limited interventions (Hamilton, 1914; Oliver, 1914; Weston, 1900).

There is now a relatively large and established literature that points to the short-term and long-term impacts of lead exposure (Aizer et al., 2018; Aizer & Currie, 2019; Billings & Schnepel, 2018; Dave & Yang, 2022; Feigenbaum & Muller, 2016; Wodtke et al., 2022). Based on the World Health Organization's recent reports, about 30 percent of the global burden of idiopathic intellectual disability among children and about 4.6 percent of the burden of cardiovascular disease is due to cumulative lead exposure (World Health Organization, 2021). Moreover, there are about 1 million deaths in the world annually due to lead exposure, roughly half of the total deaths due to known hazardous chemicals (World Health Organization, 2022). Studies suggest that prenatal exposure to lead is associated with higher risks of pregnancy complications (Bellinger, 2005), increases in fetal death (Roy & Edwards, 2021), higher infant mortality rates (Troesken, 2008), and adverse birth outcomes (Bui et al., 2022; Dave & Yang, 2022). In the long run, prenatal and childhood exposure to lead is associated with behavioral problems (Reyes, 2015), cognitive development (Coscia et al., 2003; Dietrich et al., 1991; Schnaas et al., 2006), I.Q. (Nevin, 2000), elevated blood pressure (Farzan et al., 2018), kidney functioning (Skröder et al., 2016), crime

(Feigenbaum & Muller, 2016; Reyes, 2007), educational outcomes (Miranda et al., 2007; Sorensen et al., 2019), and old-age Alzheimer's disease (Eid et al., 2016).

Despite the relatively extensive literature on the health impacts of lead, little is known about the long-run effects of early-life and childhood lead exposure on old-age longevity. This paper aims to fill this gap in the literature. In so doing, we exploit cross-city variation in the usage of lead water pipe systems as a source of exposure to lead through contaminated water. Lead may contaminate water through erosions, dissolving, and certain chemical reactions with minerals carried by water. The leaded water is odorless, tasteless, and colorless, and even some standard detection protocols underestimate the true levels of contamination (Triantafyllidou et al., 2007).

We employ Social Security Administration death records for male individuals linked to the full count 1940 census to examine the longevity differences between individuals born in cities with some lead in their pipeline water system and cities with no lead. Several factors make lead cities inherently different than non-lead cities. During the 19th century, lead was more expensive than its closest viable alternative, iron. On the other hand, lead has several advantages, including its higher longevity, durability, ease of use and installation, and malleability (Rabin, 2008). Therefore, cities with tighter budgets might choose more easily sourced alternatives. Progressive leadership of wealthier cities with better resources to invest in long-term infrastructures were more likely to use lead. Besides, although not widespread, public health experts provided early warnings and concerns about lead poisoning in drinking water (Thresh, 1901). Local authorities might consider these concerns when choosing materials for water pipelines. These selection mechanisms to employ lead in water systems may also act in other unobserved ways to impact population health. Therefore, any comparison between lead and non-lead cities is confounded by such selection mechanisms. We employ four different identification strategies to account for these confounders.

First, we exploit the fact that the concentration of hydrogen ions in the water, i.e., water pH, affects the degree of lead solution in the water. Lead is more likely to be leached into drinking water in places where the water is more acidic, i.e., with a lower pH. Factors influencing water pH (such as algal blooms, temperature, soil organic compounds, and specific minerals) are less likely to be maneuvered by policies or other city-level characteristics. We show that those exposed to acidic water in lead cities reveal roughly a 2-month lower longevity later in life and during old age.

Second, older pipelines are more prone to corrosion. The coating of aging pipelines is also more likely to wear out compared with newer ones, facilitating lead leaching into the drinking water. Using data from the establishment of water systems in the 19th century, we show that individuals born in lead cities with older pipelines experience a reduction of 1.7 months in longevity compared with other groups.

Third, prior research provides evidence that exposure to lead in drinking water during early life and childhood is more harmful to adulthood and old-age outcomes (Billings & Schnepel, 2018; Lee et al., 2022). For a subsample of individuals who migrated from their birthplace, as observed in the 1940 census, we compare the effects of the birth city's lead status and the migration destination city's lead status, allowing us to examine the impacts during early-life/childhood versus early adulthood. We find substantially larger associations between longevity and birth-city lead status than the lead status of city of residence later in life among the subsample of internal migrants, suggesting the relevance of exposure during early life and childhood rather than early adulthood.

Fourth, local authorities' decisions to employ lead in water systems was largely based on the costs and availability of lead refineries and distilleries. This fact is binding, especially during the 19th century when transportation costs constituted a large portion of the final costs of products (Jacks et al., 2010). Therefore, access to lead manufacturing facilities creates variations in transportation costs, hence the likelihood of a city implementing lead pipelines. We exploit the distance between the city and several major lead refineries as an instrument and re-examine the association between birth-city lead status and later life longevity. We find a reduction in longevity of about 9.6 months.

The contributions of this study to the literature are threefold. First, to our knowledge, this is the first study to establish a link between early-life and childhood exposure to lead and old-age longevity. Longevity and mortality outcomes are extreme but precise measures of health. They contain more accurate information on health at older ages compared with other subjective measures of health. Besides, studies have suggested that longevity reflects an array of economic and health outcomes (Buchman et al., 2012; Chetty et al., 2016; Halpern-Manners et al., 2020; Kinge et al., 2019; Lubitz et al., 2003; Sunder, 2005). Further, understanding the long-run costs of lead exposure is important as it justifies the relatively high social costs of interventions (Pfadenhauer et al., 2016). Although the harmful impacts of lead have been known for over a century, the evidence of its long-run effects is limited. Second, with an aging water pipe infrastructure in the U.S., many cities face an elevated risk of lead-in-drinking water (Allaire et al., 2018). This has been evident in the case of the recent water crises in Flint and Newark that resulted in lead leaks in urban drinking water (Dave & Yang, 2022; Grossman & Slusky, 2019). Policy concerns about this problem can also be observed in recent expansionary policies of the government. About 1.5 percent of the $1 trillion of the infrastructure bill that was passed in November 2021 had been allocated to replacing lead pipes in the water system.

Second, this paper adds to the literature that establishes a link between early-life conditions and later-life mortality outcomes (Aizer et al., 2016; Barker, 1994, 1995, 1997; Barker et al., 2002; Goodman-Bacon, 2021; Hayward & Gorman, 2004; Karas Montez et al., 2014; Lindeboom et al., 2010; Montez & Hayward, 2011; Noghanibehambari & Fletcher, 2021; Smith et al., 2009; Van Den Berg et al., 2006, 2011).

The rest of the paper is organized as follows. Section 2 provides a review of the background. Section 3 introduces data sources. Section 4 discusses the empirical methods. Section 5 reviews the results. Section 6 concludes the paper.

2. Background

2.1. Water Projects

During the 19th century, there was a notable increase in the circulation of knowledge and understanding of the microbiology of diseases, along with a growing recognition of the relevance of ensuring clean and uncontaminated water sources for the sake of public health (APHA, 1926). During this period, the United States embarked on a series of ambitious water projects to address various challenges related to water supply and water quality. This wave of water projects was driven by a growing population, urbanization, immigration, and the need for better management of water resources. Building water and sewer systems became inevitable with the rise of knowledge about and spreading of waterborne diseases like cholera. Cities like New York, Boston, and Chicago invested in large-scale water supply systems. New York City, for instance, constructed the Croton Aqueduct (completed in 1842) and expanded it in the late 19th century to meet the increasing demand.

During these decades, the country saw diverse materials used in water pipe systems. Cast iron pipes and galvanized steel, protected by a zinc coating, were largely used for their durability, longevity, and resistance to corrosion. Another material in high demand for water pipes was lead. Several technical factors and relative advantages of lead over its alternatives made it more popular nationwide. Lead water pipes could be tightly sealed, reducing the probability of leaks and ensuring a consistent flow of water. They were also easy to install, and plumbers were familiar with their features. Other reasons were their durability, availability, and corrosion resistance. In many cities, an alloy of elements, including lead and iron, was used. Further, copper, brass, and clay pipes also had their roles, with copper gaining favor for indoor plumbing due to its corrosion resistance, while clay pipes persisted in sewer systems in some regions.

2.2. Literature Review

In this section, we review the literature on the life-cycle effects of lead exposure and discuss how each outcome could operate as a mediatory channel between early-life lead exposure and old-age longevity[4].

Medical studies suggest that pollution exposures during pregnancy change epigenetic programming, which results in a distorted growth path of the fetus (Almond & Currie, 2011; Vaiserman, 2014). Pilsner et al. (2009) provide evidence that in-utero lead exposure influences genomic DNA methylation. They argue that maternal cumulative lead burden changes epigenetic programming, increasing infants' life-cycle susceptibility to diseases. Dave & Yang (2022)

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[4] A broader literature, that we only briefly note, documents the relationship between exposure to other sources of airborne and waterborne pollution and a wide range of short-run and long-run outcomes, including infants' health outcomes, human capital formation, labor market outcomes, and adulthood health (Beach et al., 2016; Brainerd & Menon, 2014; Chay & Greenstone, 2003; Currie et al., 2013, 2014; Ebenstein et al., 2015; Greenstone & Hanna, 2014; Grossman & Slusky, 2019; Jones, 2019; Mettetal, 2019; Sanders, 2012; Smith et al., 2006, 2011, 2012; Zhang & Xu, 2016). For instance, Sanders (2012) examine the effect of prenatal pollution exposure on test scores. He employs the space-time variation in the recession of early 1980s as a source of reduction in Total Suspended Particulates (TPS). He finds that a one-standard-deviation decrease in TSP is associated with 6 percent of a standard-deviation rise in high school test scores. Fletcher & Noghanibehambari (2022) explore the effects of fetal exposure to pesticide pollution on old-age longevity. They exploit periodical emergence of cicadas as a source of shock to pesticide use in tree-crop-lands. They show that exposure to rises in pesticide use during first year of life is associated with about 2 months reduction in longevity

explore the impacts of lead leakages in drinking water during the Newark lead-in-water crisis of 2016 on infants' health outcomes. They find that pregnant mothers in affected neighborhoods are 1.5 percentage points more likely to give birth to low birth weight infants, an increase of 18 percent relative to the mean. Bui et al. (2022) explore the effects of de-leading racing cars' fuel on air quality and birth outcomes. They compare mothers' outcomes who live in the vicinity of the racetrack to those residing farther away and find that de-leading racing fuel is associated with about 100 grams of additional birth weight. Wang et al. (2017) examine the association between maternal cord blood lead levels and birth outcomes. They find negative impacts on physical measures of health at birth that vary by gender, with the most effects concentrated among male infants. Several studies document the association between measures of health at birth and later-life outcomes, including mortality and longevity (Behrman & Rosenzweig, 2004; Black et al., 2007; Flouris et al., 2009; Maruyama & Heinesen, 2020; Royer, 2009; Samaras et al., 2003).

The effects of lead can be detected in infants' later-life mental development, cognitive development, and academic achievements (Gould, 2009; Goyer, 1996; Hollingsworth et al., 2022; Hu et al., 2006; Miranda et al., 2007; Nevin, 2000; Schnaas et al., 2006; Wodtke et al., 2022; N. Zhang et al., 2013). Thomason et al. (2019) examine the impact of in-utero exposure to lead on neural connectivity. They use infants' bloodspots and functional MRI data and find that lead-exposed newborns, compared with the control group reveal lower cross-hemisphere neural connectivity. They argue that this biological pathway can explain later-life reductions in cognitive ability and other regulatory functions. Clay et al. (2019) use the U.S. Census 2000 and show that 5-year-old children residing in counties with above-median surface soil lead contamination are more likely to have cognitive difficulties, including remembering, concentrating, or making decisions. Grönqvist et al. (2020) examine the impacts of life-course exposure to lead on later-life outcomes using the phaseout of leaded gasoline in Sweden. They find consistent and large impacts on test scores, high school completion, and earnings. Billings & Schnepel (2018) explore the effects of public health interventions among children with high levels of lead in their blood samples on their outcomes. They find that interventions such as lead remediation, nutritional assessment, and medical evaluations can eliminate the negative impacts on education and test scores. Sorensen et al. (2019) explore the impact of a hazard control program, a state and local joint effort to control the levels of lead in drinking water through the Flint water crisis, on children's later-life educational outcomes. They find that the program reduces the poisoning incidence by about 70% from the baseline prevalence. Moreover, they show that each percentage-point decrease in lead poisoning is associated with 0.04 standard-deviations increase in math test scores. Aizer et al. (2018) use data from Rhode Island for children born between 1997-2005 to examine the effect of lead in blood on their test scores. They use the children's pre-school blood samples and their third-grade reading tests. They show that they show that a one-unit decrease in average blood lead level is associated with about 8 percent in the probability of being below proficient in reading. The skill developments specifically through cognitive skills and educational attainments may affect old-age longevity through several channels, such as increases in income, occupational choice, social relations, peer selection, and labor market outcomes (Buckles et al., 2016; Cutler et al., 2015; Fletcher et al., 2021; Fletcher, 2012, 2015; Fletcher & Frisvold, 2014, 2015; Fletcher & Marksteiner, 2017; Fletcher & Noghanibehambari, 2021; Lleras-Muney, 2022; Lleras-Muney et al., 2020; Lleras-Muney, 2005; Meghir et al., 2018; Savelyev, 2020; Savelyev et al., 2022).

Childhood lead burden can also affect later-life health outcomes. Studies suggest that about 90 percent of lead is stored in bones (Rosin, 2009). Because bone development is disproportionately concentrated during early-life and childhood, children with more exposure store high amounts of lead in their bones and teeth. During old ages, when individuals face decreases in bone density, lead is released from bones and injected into the bloodstream. Therefore, individuals become internally exposed to lead load. Lee et al. (2022) use data from the Health and Retirement Study (HRS) linked with the 1940 census and examine the impact of lead burden during childhood on old-age cognition. They exploit the variation in cross-city differences in water pipe materials as a source of lead exposure. They find significant effects on later-life cognition but no effect on the rate of cognition decline. There is also suggestive evidence that childhood lead exposure is associated with adulthood and old-age chronic renal disease, cardiovascular diseases, blood pressure, hypertension, and dementia (Eid et al., 2016; Farzan et al., 2018; Lin et al., 2003; Mazumdar et al., 2012; Navas-Acien et al., 2007; Opler et al., 2004; Reuben, 2018; Rosin, 2009; Skröder et al., 2016). For instance, Skröder et al. (2016) employ longitudinal data from Bangladesh to assess the association between prenatal lead burden and children's kidney function. They find that exposure to lead during late pregnancy is associated with smaller kidney volume.

In addition to these lagged effects, several studies document the direct impact of lead exposure on contemporaneous mortality outcomes. For instance, Troesken (2008) uses data from the early 20th century U.S. and shows that areas with lead water pipe systems revealed 25-50 percent higher infant mortality rates than those with non-lead water pipes. Hollingsworth & Rudik (2021) show that the use of leaded gasoline in automotive racing fuel raises blood lead rates of residents in the vicinity of racing tracks, and it is also associated with increases in elderly mortality.

3. Data Sources and Sample Construction

The primary source of data for this study comes from Social Security Administration (SSA) Death Master Files (hereafter DMF). The DMF data covers death for male individuals with a social security number who died between 1975-2005. We extract DMF from the CenSoc Project

(Goldstein et al., 2021). There are three advantages to using CenSoc-extract DMF data for the purpose of this study. First, the DMF is linked to the full-count 1940 census. Hence, we are able to extract and infer (as explained below) the city of birth. This variable is essential in examining early-life exposures that operate at a very localized level. Second, there are limited linkages between the 1940 census and several other longitudinal studies, such as the Health and Retirement Study, National Health and Aging Trends Study, Panel Study of Income Dynamics, etc. However, the resulting linked data provides a very small sample size with low power.[5] In contrast, our analysis sample contains millions of observations, allowing us to detect statistical effects and implement heterogeneity analyses. Third, the linked sample has information about a wide array of family covariates and individual characteristics. We employ this information to search for mechanisms of impact and to implement balancing tests.

We extract data on the city-level pipeline materials from Feigenbaum & Muller (2016) and Clay et al. (2014). The data contains information about the primary materials used for each city's water pipes for 553 cities across the US. In order to merge water system data with DMF records, we need to infer the city of birth for each individual. In so doing, we start by linking DMF records to the full-count 1940 census extracted from Ruggles et al. (2020). We then use cross-census linking rules provided by Price et al. (2021) to merge the DMF-census-linked data with historical census 1900, 1910, 1920, and 1930. Including the city information in 1940, we have at least one and at most five city identifiers for each individual. For instance, for a person born in 1912, we potentially can observe their census city in 1920, 1930, and 1940. If merging provides null results, we can only observe his 1940 geographic identifier. Therefore, we have between 1-3 identifiers for this cohort. We use the earliest city that is observed for each individual to use as a proxy for

[5] For instance, Health and Retirement Study provides a linked sample of 9,654 people.

the city of birth and childhood. We then merge DMF with the city-level lead database based on inferred city-of-birth. In further analyses for mechanisms of impact, we also employ a subsample of data from DMF records that are linked with World War II enlistment data extracted from Goldstein et al. (2021). This data contains information on Army General Classification Test (AGCT) scores reported by enlistment agencies. The AGCT was a standardized test used by the U.S. military to measure recruits' cognitive abilities and aptitudes during World War II. The AGCT score was the primary criterion for assigning enlistees to military tasks and positions. We use the AGCT as a measure of cognitive ability in early adulthood.

Figure 1 depicts lead versus non-lead cities in the final sample. Figure 2 illustrates a density distribution of age-at-death for individuals born in lead and non-lead cities. There are no visually discernible differences in the distribution of age-at-death between individuals born in lead versus non-lead cities. Table 1 provides summary statistics of the final sample for cities with some lead materials in their water system (lead cities, first panel) and cities without any lead compounds in the water system (non-lead cities, second panel). Individuals born in lead and non-lead cities live, on average, 874.5 (72.9) and 875.1 (72.9) months (years). The share of whites in both groups is quite comparable (96%). The share of Blacks and Hispanics in lead cities (non-lead cities) is 3.5% and 0.6% (3.8% and 2.2%), respectively. Roughly 4.8 and 3.3% of lead and non-lead cities have acidic water. Roughly 71% and 67% of mothers in lead and non-lead cities are literate, respectively. Moreover, in the sample for mechanism analysis (middle panel), we observe quite comparable statistics for selected outcomes across the two groups.

In Table 2, we document several selected city-level characteristics across both lead and non-lead groups. This data is extracted from historical censuses 1900-1940 and interpolated linearly for inter-decennial years. On average, lead cities have a higher share of whites, a lower share of Blacks, a lower share of Hispanics, and a lower share of other races. Further, both groups reveal almost identical socioeconomic index, urbanization, literacy rate, the share of married, the share of homeowners, and the number of children under five years old in households.

4. Econometric Method

We start our analysis by documenting cross-sectional correlations between birth-city lead status and later life longevity using the following ordinary least square regression:

$$DA_{icst} = \alpha_0 + \alpha_1 Lead_c + \alpha_2 X_i + \alpha_3 Z_{ct} + \theta_{st} + \varepsilon_{icst} \quad (1)$$

Where the outcome is age-at-death (measured in months) of individual i born in city c in state s and year t. The variable $Lead$ is a dummy that equals one if the individual is born in a lead city and zero otherwise. In X, we include race and ethnicity dummies as individual covariates and maternal literacy and paternal socioeconomic index dummies as parental covariates. The matrix Z contains birth-city level covariates listed in Table 2. The parameter θ represents birth-state-by-birth-year fixed effects that absorb cohort convergence in health outcomes across different states and all other time-varying state-specific shocks. Finally, ε is a disturbance term. We cluster standard errors at the birth-city and birth-year level to account for serial and spatial correlations in terms, respectively.

To account for selection caused by unobserved heterogeneity across cities, we employ two-stage least square estimations and exploit the fact that proximity to major lead refineries reduces transportation costs, which provides incentives for local authorities and policymakers to consider leaded materials for water pipe systems. The primary assumption is that the location of lead refineries does not correlate with other characteristics of cities that may contribute to population health outcomes and that their effects operate solely through the availability and use of lead in water systems. This assumption plausibly holds for several reasons. The location of lead refineries primarily depends on proximity to lead ore deposits, such as those containing galena (the primary lead mineral), which were formed over geological timescale long before human settlements. Since lead smelting required significant amounts of fuel, the location decisions also depended on the availability of energy sources such as wood or charcoal. Further, technological improvements and new innovations in the energy sector and in lead processing also interacted with the location of lead refineries. For instance, the innovations of blast furnaces and cupellation for lead smelting during the 19th century made specific locations economically feasible to establish lead refineries. These factors are less likely to correlate with influences of population health and longevity.

We operationalize our two-stage least square estimation using regressions of the following form:

$$Lead_{icst} = \beta_0 + \beta_1 LogDistRef_c + \beta_2 X_i + \beta_3 Z_{ct} + \gamma_{st} + \epsilon_{icst} \tag{2}$$

$$DA_{icst} = \alpha_0 + \alpha_1 \widehat{Lead}_c + \alpha_2 X_i + \alpha_3 Z_{ct} + \theta_{st} + \varepsilon_{icst} \tag{3}$$

Equations 2 and 3 represent first-stage and second-stage regressions, respectively. The variable $LogDistRef$ measures log of distance (in miles) to the nearest lead refinery. The parameters γ and θ are birth-state by birth-year fixed effects in first and second-stage regressions, respectively. All individual, family, and city controls are as in equation 1.

5. Results

5.1. Compositional Differences in Lead and Non-lead Status

Certain observed and unobserved characteristics of cities may correlate with their lead status. For instance, progressive state-level taxation might provide additional resources that cover the extra cost of lead implementation compared with its relatively cheaper alternatives. Further, Public health awareness and concerns among city authorities might discourage the use of lead in pipeline infrastructure. These aspects could influence population health and longevity in numerous unobserved ways, confounding our cross-sectional estimates.

Although we acknowledge the unobserved differences between lead and non-lead cities, we are curious to what extent these two groups differ based on observable characteristics. In so doing, we use a city-by-year panel extracted from decennial censuses 1900-1940 and interpolated linearly for inter-decennial years. We regress several observable characteristics on city lead status, conditional on state-by-year fixed effects. These results are reported in Table 3. Lead cities have, on average, a lower population, a higher share of whites, and a lower share of Blacks (columns 1-3). They reveal a slightly higher socioeconomic index but lower female labor force participation and literacy rates (columns 7, 8, and 10). Further, there are more families with a child under five years in lead cities than in non-lead cities (column 14). Fewer white-collar occupations per population are recorded in lead cities than in non-lead cities (column 15). There are two contrasting points in this table. First, the point estimates imply relatively small changes in the outcomes. For instance, the coefficients for the share of whites, socioeconomic index, female labor force participation rate, literacy rate, and number of children less than five years old imply a change with respect to the mean outcomes of about 0.4%, 0.3%, 1.5%, 0.9%, and 1.8%, respectively. Second, the differences are not consistent. For instance, we observe increases in the share of whites but decreases in literacy rates.

One might argue that the selection process of the final sample might add different sociodemographic and socioeconomic compositions among individuals born in lead versus non-lead cities, and those differences are not fully revealed by cross-city comparisons reported in Table 3. We address this concern by examining differences in observable characteristics of individuals in the final sample born in lead versus non-lead cities, conditional on birth-state by birth-year fixed effects. These results are reported in Table 4. Those individuals born in lead cities are more likely to be white, less likely to be black, more likely to be from low socioeconomic index families, and more likely to have literate mothers (columns 1, 2, 3, and 6). However, when we compare these estimates relative to the mean of the outcomes, we find quite small implied changes. For instance, the implied percentage changes for non-Hispanic white and mother literate are 0.6% and 1.4%, respectively. Further, they do not point to consistent differences as we observe a higher share of whites but also a higher share of families with low socioeconomic status and, simultaneously, higher maternal literacy.

5.2. Birth-City Lead Status and Longevity

Table 5 compares the longevity of individuals born within the same census region (column 1) and within the same state (column 2), conditional on individual, family, and city-level covariates. Those born in cities with lead in their water pipeline experience roughly 0.7 months lower longevity. We employ various alternative comparisons in the next several sections to extract arguably more causal associations.

5.3. Lead and Water Acidity

Acidic water may react with protective coatings and other oxide layers on the inner surface of lead pipe fixtures. Such reactions allow the materials to break down and enable lead to leach into the water supply. Acidic water can also corrode plumbing materials that have partial lead. The more the water is acidic, the faster the corrosion. Chemical reactions caused by corrosion result in the lead dissolving into the water supply. Therefore, one expects to observe higher correlations between lead status and health outcomes in cities with more acidic water if the negative associations are driven by lead exposure (Ferrie et al., 2012; Kim et al., 2011). We use city-level pH data in 1954 reported by Lohr & Love (1954a) and Lohr & Love (1954b) to infer whether the water is acidic (i.e., pH<6.5). We interact a dummy indicating acidic water with the right-hand side variables and report the results in Table 6. On average, individuals born in lead cities with acidic water experience 1.8 months lower longevity. This is about 3.2 times larger than the difference in longevity of individuals in lead cities with non-acidic water and non-lead non-acidic cities, suggesting that the negative coefficients are likely driven by lead exposure.

5.4. Lead and Age of Water Systems

Second, older pipelines are more susceptible to corrosion, and the protective coatings on these aging pipelines are more likely to degrade over time compared to newer ones. This degradation increases the likelihood of lead leaching into the drinking water (EPA, 2024). We use the date of water system installation extracted from Baker (1897) and calculate the age of the water system based on the year of installation and the year the individual was born. We then generate a dummy variable indicating the age of the pipeline being above the sample median. We interact this dummy variable with the right-hand side variables. The results are reported in Table 7. Individuals born in lead cities with older pipelines experience a 1.7-month reduction in longevity. We do not observe a significant difference in lead versus non-lead cities for the below median sample. Also, there are no discernible differences in the longevity of individuals born in cities with old versus new pipelines. The evidence of this table also points to lead exposure as the driver of the negative coefficients and that such effects are significant and economically meaningful.

5.5. Early versus Mid-Life Exposure

As mentioned in section 2.2, lead is primarily stored in bones and teeth. Since bone development is concentrated in childhood years, children with high exposure accumulate more lead in their bones and teeth. In old age, as bone density decreases, this lead is released into the bloodstream, causing internal exposure. This biological mechanism implies the relevance of exposure during earlier years of life compared to adulthood years for the latent impacts on old-age longevity.

In a similar line of argument, studies that examine the long-term effects of environmental exposures usually point to the relevance of certain critical ages during early life and childhood (Almond et al., 2018; Almond & Currie, 2011). One potential implication is that we may observe discernible differences in lead-longevity correlations based on the age group of exposure. However, city-level lead status does not change over time in our sample period. One solution is to look at the sample of individuals who migrate from the city of birth to another city with a different lead status. To implement such comparisons, we focus on the subsample of migrants who belong to birth cohorts of 1920-1940. Therefore, we have information on lead status in 1940 (early adulthood exposure) as well as lead status at birth (early life exposure). The results are reported in Table 8. For this subsample, the difference in longevity based on birth-city lead status is about 2.6 months, conditional on controls and fixed effects (column 1). In column 2, we add 1940 city fixed effects to compare individuals born in different lead-status cities who migrated to the same city. The estimated coefficient is almost identical to that of column 1, suggesting that the destination city characteristics do not confound the estimates of column 1. In column 3, we compare lead status in birth-city and early-adulthood-city for individuals who migrated to another city with a different lead status than their birth-city. We observe a considerably larger coefficient for birth-city than the 1940 city lead status, implying the relevance of early-years exposures rather than later childhood/early adulthood exposures.

5.6. Two-Stage Least Square Estimations

The results of the first stage regressions of equation 2 are reported in columns 1-2 of Table 9. Doubling the distance between birth-city and the closest lead manufacturing and refinery is associated with a 21.6 percentage points increase in the likelihood of lead status, off a mean of 0.39. This is a large impact, implying a 53% increase from the baseline. The second stage regressions of equation 3 are reported in columns 3-4. The fully parameterized regression of column 4 suggests that birth-city lead status is associated with 9.6 months lower longevity. This is roughly nine times larger than the OLS coefficients of Table 5. Although the larger magnitude points to underestimated coefficients in OLS regressions, it also provides Local Average Treatment Effects (LATE). It picks up on the variations induced by specific locations of lead refineries and the degree to which cities in the vicinity of these refineries consider their proximity and their decisions about the implementation of lead in pipelines. Therefore, we should exercise caution in interpreting the results as the LATE coefficients only identify treatment effects among the subset of compliers.

One way to understand the magnitude of the estimated effect of Table 9 is to compare it with the documented effects of other shocks on longevity in studies that employ similar data, time periods, historical settings, and outcomes. For instance, Noghanibehambari & Fletcher (2023) investigate the effects of early life exposure to the Dust Bowl of the 1930s on old-age male longevity and find a reduction of about 2.5 months for individuals whose fathers are farmer and have higher exposure to the topsoil erosion due to the Dust Bowl. Since the Dust Bowl represented an unprecedented environmental catastrophe with large and long-lasting shocks to agricultural income and land value, the fact that the effect of lead exposure is about 3.8 times larger than exposure to the Dust Bowl is quite significant and policy-relevant.

Our results are also comparable to those of other studies examining the effects of exposure to toxic substances and hazardous chemicals on later life outcomes. For instance, Fletcher & Noghanibehambari(2024) investigate the impacts of early-life exposure to agrichemicals and pesticides on later-life male longevity using the emergence of cicadas between 1920-1940 as a measure that increases pesticide use in the agricultural sector. They document a reduction of about one year in the longevity of those whose fathers are employed in the agricultural sector. This effect is comparable to the effects of lead exposure, documented in Table 9.

5.7. Sociodemographic Heterogeneity

In Table 10, we examine the heterogeneity in two-stage least square estimations based on race and maternal literacy status. Among whites, we observe a reduction of 9.7 months in longevity. However, we observe an insignificant decrease of 3.6 months among Blacks. Between 1900-1940, black infant mortality rates were substantially higher than white infant mortality rates (Eriksson et al., 2018). Additionally, there is evidence that lead exposure during the early decades of the 20th century in the U.S. was associated with increases in infant mortality rates (Clay et al., 2014). Further, there is evidence that at considerably high infant mortality regimes, selection pressures dominate scarring effects to influence long-term outcomes (Nobles & Hamoudi, 2019). Therefore, one argument for the smaller association among Blacks is that the higher infant mortality regime experienced by Blacks during this period enables a degree of selection dominance over scarring, hence the overall impact becomes smaller than that of whites who experience lower selection pressures.

Moreover, we observe quite comparable coefficients among individuals with literate and illiterate mothers (columns 3-4). This fact suggests that lead-longevity associations are possibly primarily driven by biological mechanisms and reveal a lower degree of interaction with other social determinants of health.

5.8. Robustness Checks

In Table 11, we examine the robustness of the two-stage least square results to alternative specifications and functional forms. In column 1, we add a wide array of additional city-level covariates, including the share of different age groups, the share of different race groups, prohibition status (of the county where the city is located), and suffrage status. The estimated coefficient is almost identical to that of the main results.

To account for seasonality in birth outcomes and later life outcomes as well as seasonality in mortality outcomes (Vaiserman, 2021; Xuan et al., 2014), we add dummies for birth month and death month into our regressions. The estimated coefficient (reported in column 2) is quite comparable to the main results.

In column 3, we replace the outcome with log age-at-death. Birth-city lead status is associated with a 1.1% increase in age-at-death, almost identical to the implied percentage change of the coefficient in column 4 of Table 9. In columns 4-6, we replace the outcome with dummy variables indicating longevity beyond 65, 70, and 75, respectively. Compared with the mean of the outcomes, the estimated coefficients imply a change of roughly 3.4%, 5.2%, and 7.9%, respectively. The effects become larger as individuals reach older ages, suggesting the latent impacts of lead exposure during earlier years of life.

5.9. Candidate Mechanisms

Several strands of research suggest that early-life and childhood exposure to pollution, and specifically lead burden, may affect skill formation, human capital accumulation, and labor market outcomes (Beach et al., 2016; Currie et al., 2014; Sanders, 2012; Sorensen et al., 2019; Taylor, 2022; Zhang & Xu, 2016). On the other end, studies point to the influence of income, socioeconomic status, and educational attainments in determining old-age mortality outcomes (Cutler et al., 2006; Fletcher, 2015; Lleras-Muney, 2005; Mazumder, 2008; Meghir et al., 2018; Miller & Bairoliya, 2021). Therefore, we would expect to observe changes in the trajectory of education and socioeconomic status as mediatory pathways between early-life lead exposure and later-life longevity. We focus on individuals above age 19 and examine their characteristics in the 1940 census employing two-stage least-square estimations of equations 2 and 3. The results are reported in Table 12. We observe reductions in education, measures of socioeconomic status and occupational standing, and wage income. Birth-city lead status is associated with 0.2 lower years of schooling, a 29.6% reduction in any college education, an 11.2% reduction in the socioeconomic index, a 3.9% reduction in occupational income score, a 14.7% reduction in wage income, and a drop in income percentile of about 1.7 units. Finally, in column 7, we use World War II enlistment data and examine the effects on AGCT score as a proxy for cognitive and aptitude abilities. We find that birth-city lead status is associated with a 4.7 units lower AGCT score, off a mean of 75.5. This effect is equivalent to a reduction of about 6.3% with respect to the mean.

Halpern-Manners et al. (2020) examine the effects of education on longevity and document that each additional year of schooling is associated with about 3.4 months of higher longevity. Therefore, the reduction in years of schooling observed in column 1 implies a drop in longevity of about 0.7 months. This is only 7.4% of the overall effects of lead status and longevity in column 4 of Table 9. Fletcher & Noghanibehambari (2023) document that college education is associated with about 1.3-2.7 years of higher longevity. Based on column 2 of Table 12 and their estimates, one can calculate that birth-city lead status is associated with 4.5-9.4 months lower longevity. This is about 46-98% of the observed effects in Table 9. Therefore, although reductions in human capital are a likely mechanism, decreases in attaining higher levels of education are possibly a more important channel of impact.

Chetty et al. (2016) examine the association between income and longevity using the universe of death records and tax returns in the U.S. and document that each additional income percentile is associated with about 1.4 months higher longevity. Therefore, the coefficient of column 6 in Table 12 implies a 2.4-month increase in longevity. This is about 25% of the observed reduced form effects of Table 9.

6. Conclusion

Despite considerable efforts to improve water quality, many Americans are still at risk of lead in their drinking water. This is primarily due to materials used in water system pipelines. There are estimates that between 10-13 million service lines are based on leaded materials (Cornwell et al., 2016). Roughly half of the country's drinking water contains lead levels above the standard thresholds set by the American Academy of Pediatrics (NRDC, 2021). With aging water pipes, the dissolution of lead and water contamination has become a public health threat. Therefore, it is of policy relevance to examine the full costs of lead exposure, specifically among vulnerable populations.

In this paper, we explored the long-lasting impacts of exposure to lead in water pipes on later-life longevity. Overall, we documented the negative influences of lead exposure on later-life old-age longevity. The fact that the negative associations are larger in cities with acidic water and older pipeline systems contributes to our claim that reductions in longevity are driven by lead exposure in water systems. These estimates suggest that birth city lead status is associated with reductions in longevity of about 1.6-1.8 months. Further, using the sample of migrants, we found a substantially larger negative influence of lead status of birth-city rather than city of residence in later life, implying the relevance of exposure during earlier years of life. Our preferred estimation strategy relied on two-stage least square estimations that exploited proximity to lead refineries which lowers the cost of lead transportation as the instrument. We found that birth-city lead status is associated with roughly 9.6 months lower longevity. This effect is quite robust across alternative specifications and functional forms. Further, we provided empirical evidence to show that a significant portion of these reductions in later life longevity are driven by reductions in education, specifically higher educational levels.

In the U.S., male life expectancy increased from 46.3 in 1900 to 60.8 in 1940 (O'Neill, 2021). The negative intent-to-treat effects of full exposure to lead in drinking water offsets about 1%-5.5% of the overall health benefits that resulted in rises in life expectancy across cohorts of 1900-1940.[6] In the final sample, cohorts who were born in lead cities counted as 783,483 individuals. Using the estimated effects of the paper across different identification strategies, we calculate roughly 104.5-626.8 thousand life-years lost due to the use of lead in water pipes in the early part of the 20th century. We can monetize this value by incorporating the Value of Statistical Life (VSL) estimates. Some studies suggest using a VSL of about $10 million (in 2020 dollars) (Kniesner & Viscusi, 2019). The average longevity in the final sample is 72.9 years. A simple calculation suggests each life year's value is around $137.2 thousand. Using the estimated life years lost in the value of each statistical life, we can estimate a loss of roughly $14.3-$85.9 billion (in 2020 dollars) due to reductions in longevity as a result of exposure to lead in earlier years of life. We should note that this effect does not capture the life years lost due to fetal deaths, infant

[6] In this section, we use the range of effects across different identification methods in the paper. Specifically, we use the range of coefficients of Table 6 through Table 9, i.e., 1.6 – 9.6 months.

mortality, and premature mortality as a result of the early-life lead burden (Clay et al., 2014; Roy & Edwards, 2021; Troesken, 2008).

Although we used lead service lines as the measure of exposure, we should note that significant efforts have been made to lower population-level lead exposure, such as the Safe Drinking Water Act of 1974 and the Lead and Copper Rule of 1991. There are estimates that the efforts since 1970 resulted in a reduction of about 94% in blood lead levels across the U.S. population aged 1 to 74 (Dignam et al., 2019). Through these efforts, a substantial portion of net service lines have been replaced. The estimates, however, suggest that between 15 to 22 million people are still using lead-containing service lines in the U.S. (Cornwell et al., 2016).

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Tables

Table 1 - Summary Statistics

	Lead Cities		Non-Lead Cities	
	Mean	SD	Mean	SD
DMF-Census Data:				
Death Age (Months)	874.4525	125.2236	875.0655	126.3523
Birth-year	1918.3478	9.69	1918.477	9.7149
Death Year	1991.224	8.724	1991.4034	8.7156
White	.964	.1863	.9585	.1995
Black	.0354	.1848	.0379	.1911
Hispanic	.0057	.075	.0219	.1465
Acidic Water	.0479	.2135	.0333	.1795
Log Distance to the Closest Lead Refinery	4.9128	.8197	4.0046	1.3257
Father SEI Missing	.1175	.3221	.1371	.3439
Father SEI below Median	.4602	.4984	.4399	.4964
Father SEI above Median	.4222	.4939	.423	.494
Mother literate	.7128	.4525	.6734	.469
Mother literacy missing	.2297	.4206	.2537	.4351
Observations	783,483		1,191,919	
Sample for Mechanism Analysis:				
Years of Schooling	10.6018	2.83	10.7018	2.9414
Years of Schooling < 9	.2781	.4481	.281	.4495
Years of Schooling < 12	.5541	.4971	.545	.498
Socioeconomic index	33.4825	21.6874	35.0934	22.1391
Occupational income score	26.6185	9.2452	26.9556	9.7116
Log wage income	6.7657	.8659	6.8019	.8723
Income percentile	59.6751	31.5305	59.9709	32.0105
Observations	479,544		724,787	
DMF-World War II Enlistment Data:				
AGCT score	77.6849	46.1731	74.1283	48.3585
Observations	8,238		13,656	

Table 2 - Characteristics of Lead And Non-Lead Cities in the Final Sample

	Lead Cities		Non-Lead Cities	
	Mean	SD	Mean	SD
Population	67846.856	137855.76	80095.374	380227.22
Share of whites	.937	.1097	.9092	.139
Share of Blacks	.0622	.1099	.0879	.14
Share of Hispanics	.0032	.0092	.0131	.0545
Share of other races	.0009	.0034	.0029	.0089
Share of females	.5033	.0242	.5055	.0269
Average socioeconomic index	31.4101	4.644	31.4871	4.1679
Female labor force participation rate	.264	.1019	.2806	.1066
Share of married	.5807	.0405	.5796	.0431
Literacy rate	.7064	.3085	.722	.347
Urbanization rate	.99	.08	.994	.0628
Share of institutionalized	.0057	.0214	.0047	.0134
Share of homeowners	.4458	.1198	.4323	.1081
Number of children less than five years old	.3416	.0881	.3267	.0866
White-collar occupations per capita	.0494	.0225	.0521	.024
Farmers per capita	.0072	.0113	.0098	.015
Other occupations per capita	.9401	.0264	.9346	.0302
Observations	9,236		12,904	

Table 3 - Differences in City-Level Characteristics of Lead and Non-lead Cities

	Outcomes:			
	Population	Share of whites	Share of Blacks	Share of Hispanics
	(1)	(2)	(3)	(4)
Lead	-24261.995***	.00407***	-.00414***	-.00054***
	(5780.0711)	(.00075)	(.00075)	(.00017)
Observations	21882	21882	21882	21882
R-Squared	.02436	.85314	.85614	.40625
Mean DV	7.5e+04	0.921	0.077	0.009
	Share of other races	Share of females	Socioeconomic index	Female labor force participation rate
	(5)	(6)	(7)	(8)
Lead	.00006	-.00267***	.09943*	-.00483***
	(.00004)	(.00032)	(.06016)	(.00089)
Observations	21882	21882	21882	21882
R-Squared	.59563	.28752	.25171	.69601
Mean DV	0.002	0.505	31.411	0.273
	Share of married	Literacy rate	Urbanization rate	Share of institutionalized
	(9)	(10)	(11)	(12)
Lead	.00028	-.00724**	-.0051***	.00083***
	(.00048)	(.00349)	(.0011)	(.00026)
Observations	21882	21882	21882	21882
R-Squared	.44071	.55696	.10789	.10583
Mean DV	0.580	0.715	0.992	0.005
	Share of homeowners	Number of children less than five years old	Employed in white-collar occupations per capita	Employed in all other non-farm occupations per capita
	(13)	(14)	(15)	(16)
Lead	-.0034**	.00626***	-.00138***	.001***
	(.00141)	(.00095)	(.00033)	(.00037)
Observations	21882	21882	21882	21882
R-Squared	.40899	.52537	.22993	.28829
Mean DV	0.438	0.333	0.051	0.937

Notes. Standard errors, clustered on city and year, are reported in parentheses. All regressions include state-by-year fixed effects and are weighted using city-level population.
*** p<0.01, ** p<0.05, * p<0.1

Table 4 -Balancing Tests: The Difference in Sociodemographic Characteristics of the Final Sample Based on Birth-City Lead Status

	Outcomes:						
	Non-Hispanic white	Non-Hispanic black	Father socioeconomic index below median	Father socioeconomic index above median	Father socioeconomic index missing	Mother literate	Mother literacy missing
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lead	.00589***	-.0028***	.01627***	-.00895***	-.00732***	.00999***	-.00923***
	(.00057)	(.00048)	(.00155)	(.00144)	(.00079)	(.00139)	(.00082)
Observations	1975397	1975397	1975397	1975397	1975397	1975397	1975397
R-Squared	.13124	.11129	.01341	.00871	.03038	.35102	.45818
Mean DV	0.946	0.036	0.448	0.423	0.129	0.689	0.244

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. All regressions include birth-state by birth-year fixed effects.
*** p<0.01, ** p<0.05, * p<0.1

Table 5 - The Correlation between Birth-City Lead Status and Old-Age Longevity

	Outcome: age-at-death (months)	
	(1)	(2)
Lead	-.4844**	-.6619***
	(.1982)	(.2029)
Observations	1975402	1975397
R-Squared	.404	.4047
Mean DV	874.822	874.822
Birth region by birth-year F.E.	✓	✓
Controls	✓	✓
Birth-state by birth-year F.E.		✓

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.
*** p<0.01, ** p<0.05, * p<0.1

Table 6 - Heterogeneity in the Correlation between Birth-City Lead Status and Old-Age Longevity Based on Finished Water pH

	Outcome: age-at-death (months)	
	(1)	(2)
Acidic × Lead	-2.2793***	-1.8219**
	(.7696)	(.7867)
Lead	-.3713*	-.5622***
	(.2045)	(.2109)
Acidic	.0109	.6116
	(.5488)	(.5453)
Observations	1975402	1975397
R-Squared	.404	.4047
Mean DV	874.822	874.822
Birth region by birth-year F.E.	✓	✓
Controls	✓	✓
Birth-state by birth-year F.E.		✓

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 7 - Heterogeneity in the Correlation between Birth-City Lead Status and Old-Age Longevity Based on Age of Water System

	Outcome: age-at-death (months)	
	(1)	(2)
Lead × Above-Median Age of Water System	-1.2357***	-1.654***
	(.4186)	(.412)
Lead	.1548	.1683
	(.2879)	(.2924)
Above-Median Age of Water System	.5083	.4538
	(.3679)	(.3534)
Observations	1975402	1975397
R-Squared	.404	.4047
Mean DV	874.822	874.822
Birth region by birth-year F.E.	✓	✓
Controls	✓	✓
Birth-state by birth-year F.E.		✓

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.
*** p<0.01, ** p<0.05, * p<0.1

Table 8 - Heterogeneity in the Correlation between Birth-City Lead Status and Old-Age Longevity Based on Age of Water System

	Outcome: age-at-death (months), Migrants of 1920-1940 Cohorts		
	(1)	(2)	(3)
Birth-City Lead	-2.57***	-2.54331***	-3.64145**
	(.83487)	(.84147)	(1.46816)
1940-City Lead			-.54957
			(1.17889)
Observations	116673	116664	32714
R-Squared	.12797	.13514	.13954
Mean DV	829.558	829.559	833.700
Controls	✓	✓	✓
Birth-state by birth-year F.E.	✓	✓	✓
1940-City F.E.		✓	

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.
*** p<0.01, ** p<0.05, * p<0.1

Table 9 - Two-Stage Least Square Estimations of Lead Status on Old-Age Longevity

	First Stage Outcome: Lead Status		*Second-Stage Outcome: age-at-death (months)*	
	(1)	(2)	(3)	(4)
Log distance to the closest lead refinery	.2058***	.2157***		
	(.007)	(.0057)		
Lead			-7.1964***	-9.5788***
			(.9152)	(.9414)
Observations	1975402	1975397	1975402	1975402
R-Squared	.2963	.4494	.4034	.4039
Mean DV	0.397	0.397	874.822	874.822
First-Stage F-Statistics			876.034	1411.912
Birth region by birth-year F.E.	✓	✓	✓	✓
Controls	✓	✓	✓	✓
Birth-state by birth-year F.E.		✓		✓

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.
*** p<0.01, ** p<0.05, * p<0.1

Table 10 - Two-Stage Least Square Estimation Results to Examine Heterogeneity across Subsamples Based on Race and Maternal Literacy

	Outcome: age-at-death (months)			
	White	Black	Literate mothers	Illiterate mothers
	(1)	(2)	(3)	(4)
Lead	-9.6809***	-3.5564	-9.6295***	-8.9984***
	(.9472)	(4.7863)	(1.0569)	(1.2082)
Observations	1897700	72952	1361104	614298
R-Squared	.3989	.4473	.2737	.4929
Mean DV	876.749	825.618	896.841	826.036
%Change	-1.104	-0.431	-1.074	-1.089
First-Stage F-Stat	1420.110	397.831	1154.244	1256.710

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. All regressions include birth-state by birth-year fixed effects and individual/family/city controls. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 11 - Two-Stage Least Square Estimations to Examine the Robustness to Additional Controls and Alternative Functional Forms

	Adding more city level controls	Adding birth month and death month fixed effects	Outcome: log age-at-death	Outcome: age-at-death > 65	Outcome: age-at-death > 70	Outcome: age-at-death > 75
	(1)	(2)	(3)	(4)	(5)	(6)
Lead	-9.54926***	-10.06815***	-.01119***	-.02608***	-.03156***	-.03217***
	(.9415)	(1.11514)	(.00114)	(.0038)	(.00383)	(.00358)
Observations	1975402	1975402	1975402	1975402	1975402	1975402
R-Squared	.40459	.40387	.40268	.25533	.29005	.2568
Mean DV	874.822	874.822	6.763	0.756	0.591	0.404
First-Stage F-Stat	1411.884	1154.755	1411.912	1411.912	1411.912	1411.912

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. The outcome in the first two columns is age-at-death measured in months. All regressions include birth-state by birth-year fixed effects and individual/family/city controls. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita. Column one adds to these covariates by including share of different age groups, share of different race groups, prohibition status, suffrage status, and birth registration area status.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 12 - Two-Stage Least Square Estimation Results to Examine Mechanism Channels

	Outcomes:						
	Years of schooling	Any college education	Socioeconomic index	Occupational income score	Log wage income	Income percentile	AGCT score
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lead	-.20737***	-.05147***	-3.88444***	-1.03803***	-.1467***	-1.73951***	-4.74597***
	(.04082)	(.00429)	(.24348)	(.08826)	(.00926)	(.24411)	(1.65951)
Observations	1204331	1224339	1062210	1084501	945083	1160296	21894
R-Squared	.1429	0.3626	.13678	.1065	.28861	.18785	.27821
Mean DV	10.662	0.1725	34.451	26.821	6.787	59.852	75.467
%Change	-1.945	-29.651	-11.275	-3.870	-2.161	-2.906	-6.289
First-Stage F-Stat	836.940	841.800	830.303	836.755	820.148	847.189	423.143

Notes. Standard errors, clustered on birth-city and birth-year, are reported in parentheses. All regressions include birth-state by birth-year fixed effects and individual/family/city controls. Controls include dummies for race and ethnicity, dummies for paternal socioeconomic index, dummies for maternal literacy, and birth-city covariates, including share of whites, share of blacks, share of Hispanics, share of other races, share of females, average socioeconomic index, female labor force participation rate, share of married, literacy rate, urbanization rate, share of institutionalized, share of homeowners, number of children less than five years old, employment in white-collar occupations per capita, farmers per capita, and employment in all other occupations per capita. The sample is restricted to individuals aged more than 18.

*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Figures

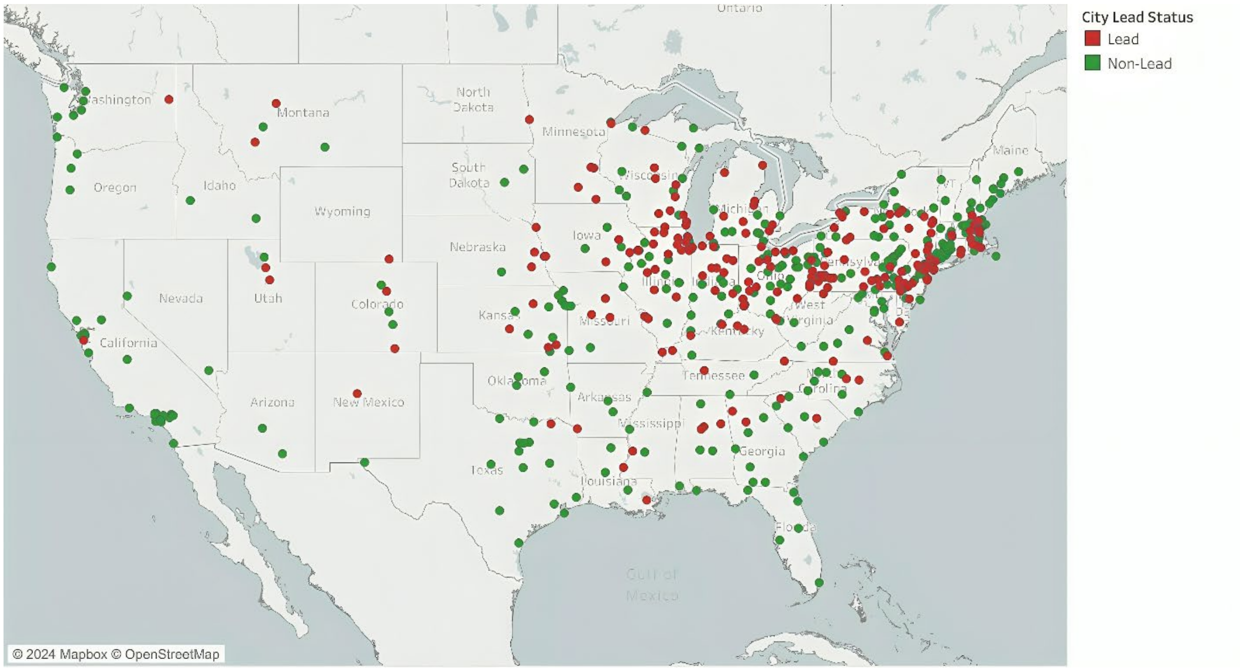

Figure 1 - Distribution of Cities in The Final Sample Based on Lead Status

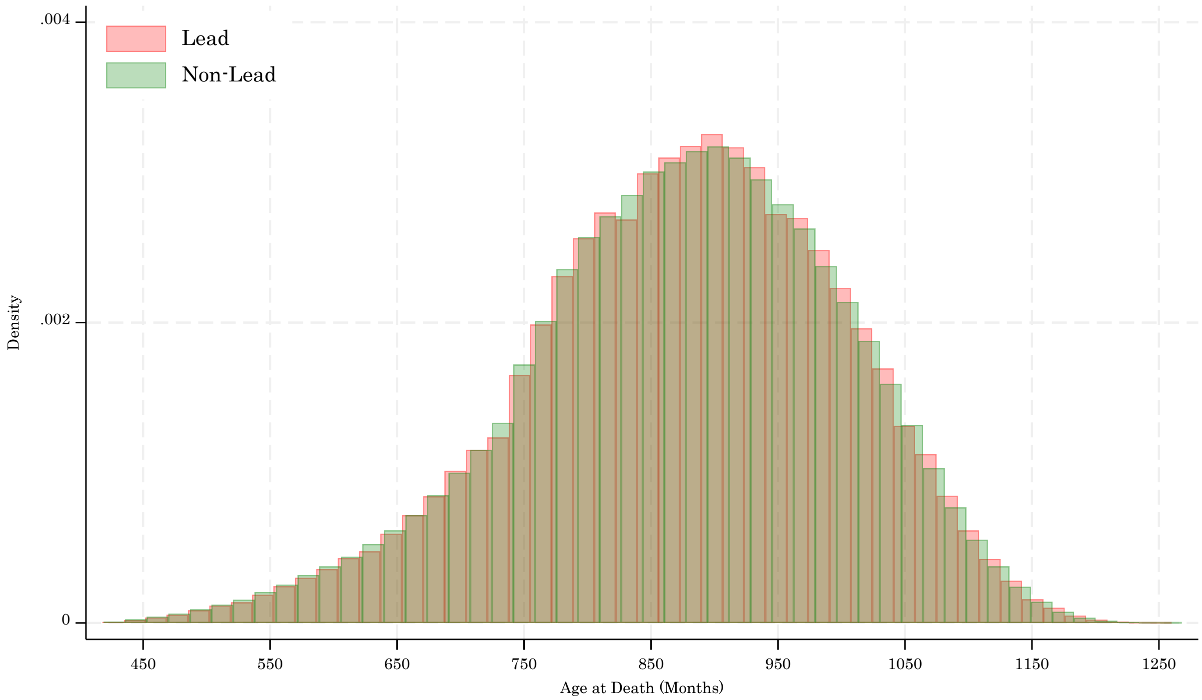

Figure 2 - Density Distribution of Age-at-Death in the Final Sample Based on Birth-City Lead Status