Burying the Lead:
Effects of Public Lead Service Line Replacements on Blood Lead Levels and Property Values

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Abstract

Despite the well-known health consequences of lead exposure, an estimated 6 to 10 million lead service lines still deliver drinking water to homes throughout the US. Disadvantaged communities are disproportionately exposed to lead service lines, contributing to health and human capital disparities. This paper studies the effects of public lead service line replacements using children's blood lead test data with confidential address information, home sales data, and geocoded public service line installation data from Rhode Island. Replacing public lead service lines significantly reduces child blood lead levels by about 0.4 $\mu g/dL$, or 13 percent, and increases the price of home sales by 7-8 percent, indicating that homeowners value these replacements.

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Lead is a neurotoxin that causes damage to the brain and nervous system, developmental delays, seizures, and, at high levels, death. Lead exposure in childhood has been linked to negative impacts on cognitive function, test scores, human capital, and earnings (Clay et al., 2019; Sorensen et al., 2019; Grönqvist et al., 2020; Aizer et al., 2018; Rau et al., 2015). Lead exposure can also lead to behavioral problems, such as criminal activity, school suspensions, and juvenile detention (Aizer and Currie, 2019; Feigenbaum and Muller, 2016; Reyes, 2015, 2007). Because lead can cross the placental barrier, it can also impact fertility and birth outcomes (Clay et al., 2021; Dave and Yang, 2022; Grossman and Slusky, 2019). The EPA and CDC agree that no level of lead exposure in children is considered "safe."

Despite these well-known health consequences of lead exposure, an estimated 6 to 10 million lead service lines still deliver drinking water to homes throughout the US and about 15 to 22 million individuals are served by water systems with lead lines. Lead crises, such as those in Washington, DC, Flint, MI, and Newark, NJ, have captured the nation's attention and underscored the persistence of this health threat to drinking water supplies. Disadvantaged communities are disproportionately exposed to these lead service lines, which may contribute to existing health and human capital disparities and leaves these households vulnerable to another public health emergency. Although $15 billion was recently dedicated to replacing lead service lines throughout the US as part of the Infrastructure Investment and Jobs Act of 2021, we know very little about the effect of lead service line (LSL) replacements on direct measures of health, such as child blood lead levels (BLLs), or on indirect measures of households' valuation of these replacements.

This paper is the first to study the direct and indirect causal effects of public lead service line replacements on child blood lead levels and housing prices. Address information in the blood lead testing data also provides an opportunity to study the moving behavior of all households, not just homeowners, in response to replacements. I use confidential data on child blood lead levels with address information, tax assessor data on home sales, and data on the geocoded location and timing of service line installations conducted as part of a Lead Service Line Replacement (LSLR) Program in Rhode Island. Providence Water serves 60 percent of the state's residents, about 600,000 people, and had about 25,600 LSLs in 2006. As a consequence of exceeding the EPA's lead action level, Providence Water was required to replace 7 percent of the lead service lines they owned annually, starting in 2007. From 2007 to 2010, they spent over $55 million to replace about 10,000 public-side lead service lines. These replacements were determined by the utility, rather than homeowner, which provides a plausibly exogeneous source of variation in LSL replacement.

The effect of LSL replacements on child blood lead levels is not obvious, because mineral scale on the inner surface of older plumbing often prevents lead from leaching into drinking water. Child BLLs may not change if lead exposure from lead service lines is not a significant contributor to child BLLs. Child BLLs may go down if lead service lines are a significant contributor to elevated blood lead levels and replacements reduce lead concentration of drinking water. On the other hand, child blood lead levels could actually go up. When mineral scale is removed, disturbed, or has yet to develop, lead may leach into drinking water, potentially increasing lead in water. Although existing evidence has shown that construction from water main replacements in Chicago did not disturb LSLs enough to affect lead levels in water or children's blood lead levels (Gazze and Heissel, 2021), we lack credible causal evidence of the impact of lead service line removals on child BLLs.[1] Cross-sectional estimates from Brown et al. (2011) show that partial replacement of lead service lines is correlated with elevated blood lead levels, possibly due to disturbance of the mineral coating. However, with only cross-sectional variation, this study is unable to control for other household characteristics that may have been correlated with partial LSL replacement.

I find that replacement of public-side lead service lines significantly reduced child blood lead levels among non-movers by about 0.4 micrograms per deciliter ($\mu g/dL$), or about 13 percent from the mean. One can also compare the magnitude of this estimate to the gap in average blood lead levels for children in newer versus older homes that are most likely to have lead service lines. The effect of LSL replacement is about 31 percent of this gap, which suggests that lead exposure through drinking water is a significant contributor to children's overall blood lead levels and even partial lead service line replacements can help

[1] Whereas most water systems have already replaced lead water mains, millions of lead service lines remain in operation today. Water mains typically run under the street, whereas service lines deliver water from the water main to the customer's home and consist of public and private-owned segments. The "public" service line segment runs under the street from the property line to the water main and is owned by the water system. The "private" service line segment begins at the property line and is the responsibility of the homeowner. Figure A1 depicts a typical service line and denotes the portion of each line that is owned by the homeowner or the water system.

reduce elevated BLLs in children. I also find that LSL replacements increase home values by about 7-8 percent, suggesting that homeowners value the public-side LSL replacements. While there is no impact on the probability of a home selling after replacement, address information in the BLL testing data shows that children moved away from older homes after public-side replacements. This indicates that replacements could act as an information channel to renters that leads to avoidance through moving.

This paper makes several important contributions to the literature. First, this paper contributes to a relatively small literature on the modern-day effects of water pollution on direct measures of health in the US (Marcus, 2021b; Hill, 2018; Currie et al., 2013). Unlike air pollution, water pollution exposure is much more difficult to measure (Keiser and Shapiro, 2019). Testing for contaminants often only happens at drinking water treatment facilities and can be infrequent, making it difficult to know household-level exposure at a given time. Moreover, even when data on household-level exposure to contaminants exists, the variation is typically cross-sectional in nature or changes are endogenously determined by household decision-making and avoidance behavior. This paper exploits a unique setting with plausibly exogenous household-level variation in removal of lead service lines that rolls out over time. Because the water utility, rather than the homeowner, determined the location and timing of LSL replacements, these replacements are unlikely to be correlated with other household-level changes.

Second, this paper provides the first causal estimates of the effect of LSL replacements on child blood lead levels. Lead service lines are an important, yet understudied, source of lead exposure in children. Existing economics research on lead exposure in children has primarily focused on other channels, including leaded gasoline and lead-based paint.[2] Using variation from the phase out of lead in gasoline, the existing literature shows that lead exposure reduces cognitive function, reduces human capital accumulation, and increases crime (Grönqvist et al., 2020; Clay et al., 2019; Aizer and Currie, 2019; Reyes, 2015, 2007). Other work has documented that the continued use of lead in aviation fuel and automotive racing fuel has also negatively impacted blood lead levels in exposed communities (Hollingsworth

[2] Klemick et al. (2020) also show that Superfund site cleanups reduce the risk of elevated blood lead levels in children living near the site.

and Rudik, 2020; Zahran et al., 2017). Another strand of research has focused on the health and human capital benefits of lead paint remediation (Aizer et al., 2018; Billings and Schnepel, 2018). Jones (2012) find that a one-tenth percentage point increase in the proportion of remediated older housing units in Chicago is associated with a four-tenths percentage point reduction in the prevalence of childhood lead poisoning. These efforts to address lead exposure through de-leading gasoline and lead-based paint remediation have been the primary focus of policymakers and have been quite successful.[3] However, exposure to lead through the millions of LSLs that still deliver water to homes has received much less attention. Exposure to lead through LSLs was only recently brought to the forefront of public discussion when an estimated 6,000 to 12,000 children in Flint, MI experienced increased lead exposure through drinking water and the share of children testing positive for elevated blood lead levels more than doubled (Hanna-Attisha et al., 2016).

Most of the research on the negative effects of lead pipes comes from the early 20th century, when water distribution systems were relatively new. High water acidity in cities with lead pipes impaired cognitive performance among World War II enlistees and increased infant mortality in the early 1900s (Ferrie et al., 2012; Clay et al., 2014). In addition, Feigenbaum and Muller (2016) show that cities' use of lead service pipes exposed entire city populations to higher doses of lead and significantly increased city-level homicide rates. A smaller literature documents the modern-day impact of lead exposure through drinking water during recent lead crises in Flint and Newark on fertility and health at birth (Dave and Yang, 2022; Grossman and Slusky, 2019). This paper contributes this literature to show that lead remains a significant threat to health, even in a modern context when many believed that sediment buildup would protect lead from leaching into drinking water, and provides policy-relevant estimates of the impact of public LSL replacements on child BLLs.

Next, by studying the effect of public-side LSL replacements on the price of homes, this paper contributes to a literature on the valuation of environmental hazards using housing prices. Existing work has shown the effect of various environmental hazards on housing prices, including air pollution improvements from the Clean Air Act (Chay and Greenstone,

[3]A number of key regulations helped to dramatically reduce child blood lead levels since the 1970s, including the 1970 Lead Paint Poisoning Prevention Act, the Clean Air Act, and the Environmental Protection Agency's rules on leaded gasoline.

2005), toxic plants and hazardous waste sites (Currie et al., 2015; Gamper-Rabindran and Timmins, 2013; Greenstone and Gallagher, 2008), power plants (Davis, 2011), as well as shale gas development (Muehlenbachs et al., 2015; Boslett and Hill, 2019), among others. A much smaller literature focuses on the effect of lead hazards on home prices. For example, lead paint remediation in older homes impacts housing values and the sorting of households across homes (Gazze, 2021; Billings and Schnepel, 2017). Christensen et al. (2022) find that the lead crisis in Flint, Michigan reduced home values by 27-43 percent.

Finally, this paper contributes to a literature showing the effect of information about pollution on avoidance behaviors. Existing research has shown that individuals respond to air quality alerts (Neidell, 2004, 2009) and increase bottled water purchases in response to drinking water quality violations (Marcus, 2021b; Allaire et al., 2019; Zivin et al., 2011). Individuals may even respond to pollution information by moving (Marcus, 2021a; Currie, 2011). Bae (2012) found evidence that families with children were less likely to buy older homes after sellers were required to disclose known residential lead-based paint hazards. Importantly, estimates based on home sales and prices do not capture any impacts on renters. Renters are disproportionately exposed to lead service lines, and yet they are reliant on their landlords to pay for replacements. In practice, landlords are only required to inform residents of known lead hazards, and the service line material was commonly unknown at the time. Public lead service line replacements by the utility may have provided a channel through which renters learned about the presence of public and private lead service lines. Although the replacements I study involved removal of the public portion of the LSL, the private portion was commonly also made of lead and usually remained in place. I document an increase in the probability that a child is at a new residential address after public LSL replacement, but no change in the probability that a home is sold. I show that these children are more likely to move to newer homes without lead service lines. This suggests that renters may have received additional information about the presence of LSLs and were more likely to move in order to avoid exposure to the remaining private-side LSLs.

The rest of the paper proceeds as follows. Section 1 provides background on the health effects of lead exposure, the history of lead regulation in the US, and Rhode Island's lead regulation and lead service line replacement program. Sections 2 and 3 describe the data and the empirical strategies, respectively. Section 4 describes the results on child blood lead levels, housing prices, and behavioral responses. Finally, Section 5 discusses the findings and concludes.

1 Background

1.1 Health effects of lead exposure

Exposure to lead can occur through the skin, inhalation or ingestion. Lead quickly enters the bloodstream and is subsequently deposited in bones, soft tissues, and organs, including the brain. Lead stored in the teeth and bones accumulates over time and can be re-mobilized into the blood. Lead serves no purpose in the human body, but rather displaces or mimics necessary metals, such as calcium. Lead can affect any of the body's organs and is known to impair brain development, cognitive function, attention, short-term memory, and impulse control. Lead can also have detrimental effects on the cardiovascular, renal, and reproductive systems.

This paper focuses on lead exposure in children, as they tend to be more susceptible to lead and show signs of severe lead toxicity at lower levels than adults. Conditional on exposure, children absorb more lead than adults, and children's nervous systems are still developing. While nearly all lead in adults is excreted from the body within weeks, only about one-third of the lead in children will leave the body. Undernourished children are even more susceptible to lead, because the body will absorb more lead if other nutrients, such as calcium or iron, are lacking (Goyer, 1995; Hollingsworth et al., 2020). Even developing fetuses are at risk of lead exposure as lead can cross the placental barrier and can cause damage to the nervous system, affect behavior, and increase risk for miscarriage.

While the range and severity of the effects of lead increase with exposure levels, there is no known "safe" level of blood lead concentration (Lanphear, 2017).[4]

[4] www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

1.2 US History of Lead in Drinking Water

Although the harmful effects of lead exposure are well-known today, millions of lead service lines remain in use due to a variety of historical features. Lead service lines were regularly installed in the US for water distribution on a major scale beginning in the mid 1800s, especially in larger cities. Service lines deliver water from the water main to the customer's home and consist of two segments. The "public" service line segment runs under the street from the property line to the water main and is owned by the water system. The "private" service line segment begins at the property line and is the responsibility of the homeowner. Figure A1 depicts a typical service line and denotes the portion of each line that is owned by the homeowner or the water system.

While lead pipes were more expensive than iron, they were more durable and malleable. When originally installed, they were expected to last about 35 years, relative to 16 years for iron, and could be bent around existing structures. While early concern about the potential toxicity of lead from water passing through lead pipes is documented into the early 1900s, it was not until the 1920s that many cities started revising local and state plumbing codes to prohibit or limit the use of lead in pipes for water distribution (Rabin, 2008). Although most cities in the US were moving away from installing lead pipes by the 1920s, it was not until 1986 that Congress amended the Safe Drinking Water Act to prohibit the use of pipes, solder or flux that were not "lead free" in public water systems.[5]

Despite the prohibition of newly installed lead pipes, existing lead pipes in the water distribution systems were allowed to remain in place and many still exist today. Lead can enter drinking water when these lead plumbing materials corrode. A number of factors influence the degree to which lead enters the water, including the acidity of water, the types and amounts of minerals present, the amount of lead, the temperature of the water, the age of the pipes, the duration that water is stagnant in the pipes, and the presence of protective scales or coatings inside the pipes. Lead service lines are typically the greatest source of lead in drinking water, but lead can also be found in faucets, fixtures, and plumbing with lead

[5] At the time, "lead free" pipes were still allowed to contain up to 8 percent lead. In 2011, the definition of "lead free" was revised by lowering the maximum lead content of the wetted surfaces of plumbing products to a weighted average of 0.25 percent.

solder.

Instead of mandating the removal of existing lead pipes, the EPA issued the Lead and Copper Rule (LCR) in 1991 to attempt to control the corrosivity of the water and prevent lead leaching from pipes into drinking water. The regulation requires community water systems to test for lead in tap water by collecting samples from homes that are more likely to have lead plumbing materials. For each water system, if 10 percent of the samples from homes exceed the EPA's action level of 15 parts per billion (ppb), the water system must undertake a number of actions to control corrosion. These actions include taking additional steps to optimize corrosion control treatment, educating the public about lead in drinking water, and replacing lead service lines owned by the water system. More than 5,000 water systems violated the testing requirements of the Lead and Copper Rule in 2015, and over 1,000 systems serving nearly 4 million people reported exceeding the EPA's lead action level between 2013 and 2015 (Olson and Fedinick, 2016).

1.3 Lead in Drinking Water in Rhode Island

In Rhode Island, lead exposure through drinking water has consistently been a large concern. The aging distribution system has water mains and lead service lines dating back to the 1800s. Providence Water, the largest community water supply system in RI, routinely samples 300 locations in each compliance sample round for Lead and Copper Rule compliance. For the first 15 years after the Lead and Copper Rule was established, the 90th percentile of lead compliance samples in Providence were consistently between 10 and 15 ppb, just below the EPA's action level, as shown in Figure 1. In an effort to reduce lead levels, ProvWater commissioned a study to assess their corrosion control. Based on the EPA's research findings, the study recommended reducing the pH level of the water from 10.2 to 9.7, which was expected to be the optimal level to reduce lead solubility in water. Contrary to expectations, after this change was implemented in 2006, the 90th percentile of lead samples exceeded the action level for the first time. Between 2006 and 2017, the lead testing results were at or exceeded the lead action level in 16 of 23 testing periods. Figure 1 shows the 90th percentile of lead tests for ProvWater from 1997 to 2017.

Exceeding the lead action level in 2006 triggered the EPA's requirement for ProvWater to begin a lead service line replacement program in 2007. Water systems with 10 percent of samples exceeding the 15 ppb lead action level were required to replace 7 percent of public lead service lines per year until all were replaced or until less than 10 percent of sampled sites exceeded 15 ppb, bringing the system back into compliance. As ProvWater had 25,600 lead service lines in 2006, they were required to replace about 1,792 annually, costing about \$8 million per year. Between 2007 and 2010, ProvWater replaced about 10,000 lead service lines as part of their LSL Replacement Program. Figure 2 shows the density of service lines installed among older homes by year of installation. The figure clearly shows the dramatic rise in service line replacements between 2007 and 2010 driven by the LSL Replacement Program, which is the variation leveraged in this study.

Requirements to replace lead service lines applied only to the public portion of service lines owned by the water system. While ProvWater was required to offer to replace the property owners' portion of the service line, these private-side replacements were done at the owners' expense, which was about \$3,800 on average (Providence Water, 2021).[6] In practice, very few owners (only 1-2 percent) chose to replace their private lead service lines during this time due to the cost. Therefore, most of the service line replacements made through this program were partial lead service line replacements (PLSLR), as they typically replaced only the public lead service lines.

Starting in 2010, with the release of a new CDC study, the efficacy of partial lead service line replacements came under question. Cross-sectional estimates in Brown et al. (2011) showed partial replacement of lead service lines was associated with elevated blood lead levels, possibly due to disturbance of the mineral coating that increases lead in water. However, with only cross-sectional variation, this study could not control for other characteristics of households that may have been correlated with partial LSL replacement. Following this, the EPA's Science Advisory Board reported in 2011 that there was "inadequate" evidence to determine the effectiveness of PLSLR (US EPA, 2011). Given these concerns, the Rhode Island Department of Health granted a stay of the LSL replacement program in 2012. Since

[6] At the time, a 1% interest loan was made available, but take-up was low. In 2018, ProvWater began to offer a 3-year 0% interest loan program for homeowners to replace their private side lead service lines. This was funded through a \$1 million loan from the Rhode Island Infrastructure Bank and through additional water rate increases to customers. More recently, the loan term was extended to 5 years.

then, Providence Water has focused on increasing full LSLRs (i.e. simultaneously replacing both the public and private side) through public education efforts. Beginning in 2018, Providence Water implemented a policy to conduct only full LSLRs.

Currently, Providence Water offers free lead testing to all of their retail customers. Customers can request a lead testing kit, which is sent through the mail. Samples are returned through the mail and the results of the test are provided to the customers. Because temporary spikes in particulate lead levels are common for up to several months after construction of both partial and full LSLR, Providence Water promotes free post-LSLR lead testing for customers and provides a counter-type filter and a 6-month supply of NSF 53 certified filters.[7] To the extent that these protective actions were performed in the early years of the LSLR program, before the CDC report generated concerns about partial LSLRs, they are likely to mitigate households' exposure to spikes in lead levels immediately after LSLR. As only a 6-month supply of filters is provided, these protective actions are unlikely to persist beyond the first 6 months after replacement.

Rhode Island also has regulations targeting other sources of lead exposure, such as lead paint. Lead-based paints were banned for residential use in 1978, but homes built prior to 1978 are likely to have some lead-based paint. In Rhode Island, the Lead Hazard Mitigation and Lead Poisoning Prevention Acts require all pre-1978 non-exempt rental homes to be inspected for lead in order to obtain a "lead safe" certificate, but inspections focus primarily on lead paint and do not necessarily require testing the tap water.[8]

[7]Filters and instructions are distributed by the inspectors prior to the LSLR. The construction inspector collects the water samples, and sends them to an outside laboratory for analysis(Providence Water, 2021).

[8]Exemptions include (1) temporary housing; (2) elderly housing; (3) one, two and three-unit homes, one unit of which is occupied by the property owner; and (4) units that have been found to be lead-safe or lead-free through the proper certification. The most common types of certificates are the Certificate of Lead Conformance and the Conditional Lead Safe Certificate. The Certificate of Lead Conformance is required for most pre-1978 rental units and involves an Independent Clearance Inspection, which is limited to a visual assessment of painted surfaces and dust wipe sampling. The Conditional Lead Safe Certificate is required for properties with RIDOH violations and involves a Comprehensive Environmental Lead Inspection (CELI), which determines the presence of lead in paint, dust, soil, and water. If a CELI detects lead in drinking water, owners must label taps with a warning message in the primary language of the occupants, must provide bottled water for drinking and cooking until the water reaches a lead-safe level, and replace lead-containing pipes with lead free materials (216-RICR-5015-3.16.16).

2 Data Description

Data for this project come from several sources, including public water service lines data, census data, blood lead test results with address information, and tax parcel data on home sales. I describe each the data sources in detail below.

Service Line Data

Service line data comes from the Providence Water Supply Board (ProvWater), which serves about 60 percent of all Rhode Island residents with drinking water. These data contain the spatial location of all public service lines, year of installation for each line, line material (e.g. lead, copper, etc.), and line type (e.g. commercial, residential, etc.).[9] These data include information on only the public-side of each service line, and I limit the sample to residential lines.[10] Figure 3 shows the location of service lines. Non-lead lines are shown in light peach, lead lines that had not yet been replaced as of 2017 are shown in medium brown, and non-lead lines that were installed during the Lead Service Line Replacement program (between 2007 and 2010) are shown in dark brown.

The distribution of the percent of lead service lines within block-groups covers a wide range, as shown in panel a of Figure 4 . While many neighborhoods have very low levels of lead service lines, some neighborhoods have over 80 percent of total service lines that were likely made of lead. However, panel b shows that, conditional on having some lead service lines, the percent replaced during the LSLR Program is most likely to be 0 or 100 percent. This suggests that the replacements were concentrated in certain neighborhoods, which is visually consistent with Figure 3.

Service line data are combined with additional tax parcel data from the cities of Provi-

[9]ProvWater began converting their service line information into GIS data in the mid-2000s from both paper records and a digital work order system. The service line material for the public side of the service line was taken from the old records and transferred to the geocoded service line data. This information is updated as part of the work order process when services are added, removed, or replaced (Providence Water, 2021).

[10]Unfortunately, I lack information on private-side service line replacements and interior plumbing and fixture material, which may also be important sources of lead exposure for children. However, private-side LSL replacements were infrequent during the LSL Replacement program. Less than 2 percent of homeowners chose to replace the private portion of the service line at the same time as the public portion replacements were made, because homeowners were responsible for this extra cost, about $3,800 on average.

dence and Cranston, which contain information on the year homes were built.[11] Using year of service line installation, Figure A3 shows that lead service lines were frequently installed up until about 1937. After 1937, almost none of newly installed service lines were made of lead. This is consistent with historical records that show LSL installation was discontinued in 1937 when copper tubing was adopted (Providence Water, 2021). Therefore, homes built prior to 1937 were more likely to have had a lead service line.

Child Blood Lead Level Data

Blood lead level test results for children come from the Rhode Island Department of Health (RIDOH). These data contain all blood lead test results from 2005 to 2016 for children ages 0 to 6 years old. In Rhode Island, healthcare providers are required by law to conduct at least two blood lead screening tests on all children by the age of three. Children should then be screened annually through age six. Children between age 3 and 6 with all previous blood lead tests under 5 $\mu g/dL$ can be screened using risk assessment questions shown in Table A1. For example, children living in newer homes with fewer sources of potential lead exposure may not need to take a blood lead test. Results of blood lead tests must be reported to the RIDOH within 10 days of testing. Lead screening tests for children under age six are free.[12]

The blood lead test data include information on year tested, test result, and test method. Two types of blood lead testing methods are used. Capillary tests use a small amount of blood taken from the capillaries close to the skin in a child's arm, finger, or heel. Venous tests require a withdrawal of blood from the child's arm and are more accurate than capillary tests. The main estimates restrict the sample to venous test results, but are robust to including capillary tests as well.

Confidential information on residential addresses of children allow linkages between children and public water service lines. Importantly, a unique identifier for each child makes it possible to observe blood lead test results for the same child over time. The sample is restricted to non-moving households. I observe the age at which each test was taken and, if

[11] Over 60 percent of child observations are from locations in Providence and Cranston. Tax parcel data was not available for other cities that were served by ProvWater, such as North Providence, Johnston, and Pawtucket. Analysis using year built data is therefore based on the smaller sample of parcels located in either Providence or Cranston.

[12] RI insurance companies and Medicaid fully cover the costs of lead tests, and children without insurance can obtain a free test at St. Joseph Hospital Health Center.

there are multiple tests per year of age, I measure blood lead level as the average of all tests for a child at that age. I show that the results are robust to using the minimum value or maximum value as well.

Home Sales Data

Data on home sales come from the Rhode Island Tax Assessor and include sales from 2002 to 2018. I restrict the sample to residential homes and arms-length sales. Spatial information on tax parcel locations are used to combine home sale data with service line replacements. I exclude sales for new construction homes, defined as homes built after 2000 where the year built is equal to the year of service line installation.

Service lines installed at old homes during the LSLR Program, from 2007 to 2010, are most likely to be lead service line replacements. I focus on these treatment cohorts and define installations as part of the LSLR Program if they occur between 2007 and 2010 at homes built before 1937. Service line replacements before or after the program, or at new homes, may be lead service line replacements or may be associated with home remodels or new construction. These non-LSLR Program installations may be endogenous to home remodels.

Data on home characteristics include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade.[13] I condition on these covariates in all regressions to account for differential trends in home prices based on house characteristics.

Census Data

Census data is used to understand the distribution of lead service line exposure and replacements across demographic groups in Providence. Data comes from the 5-year sample of the American Community Survey (ACS) from 2013. Observations are at the block-group level and include information on median year homes were built, household size, home ownership type (owned, mortgaged, rented, or vacant), household type (single headed, married, single person, or non-family), education level, unemployment, public assistance, median household income, race, and presence of children.

[13]Grade is the original quality and construction of the house when built.

3 Empirical Strategy

I exploit variation in child exposure to lead service lines from differential timing and location of lead service line replacements. The vast majority of these replacements were conducted as part of the Lead Service Line Replacement program, a requirement which was triggered when 10 percent of tap samples exceeding the 15 ppb lead action level in 2006. As the decision regarding time and location of the public lead service line replacements was made by the utility owner, rather than the homeowner, it is likely to be exogenous to other household-level changes. Moreover, very few households (less than 2 percent) chose to replace the private portion of the service line at the same time as the public portion replacements were made, because homeowners were responsible for this extra cost, about $3,800 on average. As other lead-reducing interventions tend to be even more costly, it is unlikely that homeowners were simultaneously investing in other lead-related interventions.[14]

Given this variation in treatment timing and location from lead service line replacements, a traditional two-way fixed effects (TWFE) design would estimate the following,

$$BLL_{ia} = \beta^{TWFE} AfterInstall_{ia} + \pi_i + \delta_a + X + \varepsilon_{ia} \tag{1}$$

where the outcome is the average blood lead level for child i at age a for the panel of children tested between ages 0 and 6. The main variable of interest, $AfterInstall_{iat}$ is equal to one after a service line is replaced. The sample is restricted to non-moving households in order to abstract away from any endogenous moving behavior, which I examine directly in a separate analysis. Age indicators, δ_a, control for trends and shocks common to all children at different ages. Additional controls could be included in the vector X.

However, a recent literature has demonstrated that the estimate given by β^{TWFE} can only be interpreted as a weighted average of causal effects, and problematically, some of these weights can be negative (Callaway and Sant'Anna, 2020; Goodman-Bacon, 2021; Borusyak and Jaravel, 2017; De Chaisemartin and d'Haultfoeuille, 2020). In the presence of dynamic treatment effects, for example, comparisons of newly treated children to already treated

[14]For example, the EPA estimates that lead-based paint removal costs about $8 to $15 per square foot or about $9,600 to $30,000 for a 1,200 to 2,000 square foot house.

children are not a valid comparison, as already treated children may still be responding to their past treatment and, therefore, cannot provide a valid counterfactual to represent potential outcomes in the absence of treatment. As lead in the body can accumulate over time and can be re-mobilized into the blood, it is likely that the effect of lead service line replacements may grow over time.

Therefore, I follow Callaway and Sant'Anna (2020) to summarize the effect of lead service line replacements on child blood lead levels by estimating group-time average treatment effects, $ATT(g,t)$, for groups g and time periods t where there are T periods. Groups comprise all units that are treated at a particular age. I drop all units that were already treated by the time they were first observed in the data. These already treated units cannot be used as valid counterfactuals in the presence of dynamic treatment effects. Because there are lead service line replacements made for children at each age from 1 to 5, there are 5 timing groups. As the LSL Replacement program drove the majority of these replacements, I also show the results are similar when focusing only on treatment defined as replacements made during this program.

I estimate the group-time average treatment effect for each group g in each time period t by comparing units in g to one of two control groups: never treated units or units that were not-yet-treated in time t. Depending on the comparison group, I assume that the blood lead levels of children in houses with LSL replacements would have trended the same in the absence of treatment as the blood lead levels of children of the same age in houses with never replaced LSL or not-yet-replaced LSL (see Assumptions 5 and 6 in Callaway and Sant'Anna (2020)). To account for general trends in blood lead levels over time, I also condition on calendar year using the doubly robust estimator (Callaway and Sant'Anna, 2020; Sant'Anna and Zhao, 2020). Equations 2 and 3 show the group-time average treatment effect for group g at time t using the never treated and not-yet-treated units as a comparison group, respectively,

$$ATT^{nev}(g,t) = \mathbb{E}[BLL_t - BLL_{g-1}|G_g = 1] - \mathbb{E}[BLL_t - BLL_{g-1}|C = 1] \tag{2}$$

$$ATT^{ny}(g,t) = \mathbb{E}[BLL_t - BLL_{g-1}|G_g = 1] - \mathbb{E}[BLL_t - BLL_{g-1}|D_t = 0] \tag{3}$$

where BLL_t is the blood lead level at time t, G_g is an indicator equal to one for units in treatment group g, C is an indicator equal to one for the never treated units, and D_t is an indicator equal to one after treatment and equal to zero for not-yet-treated units.[15] I estimate $ATT^{nev}(g,t)$ and $ATT^{ny}(g,t)$ with $\widehat{ATT^{nev}(g,t)}$ and $\widehat{ATT^{ny}(g,t)}$, which are the sample analogues of equations 2 and 3. Standard errors are clustered at the child level with a multiplier bootstrap procedure (see Callaway and Sant'Anna (2020) for details). Unlike the commonly used pointwise confidence bands, this approach obtains simultaneous confidence bands that asymptotically cover the entire path of the group-time average treatment effects with a fixed probability and takes into account the dependency across different group-time average treatment effect estimators, which is arguably more suitable for visualizing the overall estimation uncertainty.

In practice, $\widehat{ATT^{nev}(g,t)}$ and $\widehat{ATT^{ny}(g,t)}$ estimate a classic 2x2 difference-in-difference without variation in treatment timing by comparing the relative difference in outcomes for group g and a control group (either not-yet-treated or never treated units) between period t and the reference period prior to treatment, $g-1$.

Group-time average treatment effects are aggregated by simple aggregation, event-time aggregation, and group aggregation. First, simple aggregation summarizes an overall effect:

$$\theta^{overall}_{simple} = \frac{1}{\kappa}\sum_{g\in G}\sum_{t=1}^{5}\mathbb{1}(t\geq g)ATT(g,t)P(G=g|G\leq T) \tag{4}$$

where $\kappa = \sum_{g\in G}\sum_{t=1}^{5}\mathbb{1}(t \geq g)P(G = g|G \leq T)$, which ensures that the weights on $ATT(g,t)$ in the second term sum to one. This method of aggregating average treatment effects eliminates the negative weighting issue that plagues the TWFE estimate of β^{TWFE} from equation 1 in the presence of dynamic treatment effects.

Next, I use the event-study style aggregation to look at trends prior to treatment and the evolution of the effects after treatment. Null estimates in pre-treatment periods give support for the assumption that parallel trends would have continued in the absence of treatment.[16]

[15]Note that, unless otherwise indicated, I impose the "no-anticipation" assumption, such that I assume the lead service line replacements are unanticipated. This is a reasonable assumption as the choice to replace a particular lead service line is made by the utility owner, not the homeowner.

[16]Note that when using the never treated comparison group (invoking Assumption 4 of Callaway and Sant'Anna (2020)), the assumption does not restrict pre-treatment trends across groups. Whereas using the

Let e denote event-time (i.e. $e = t - g$ which is the time elapsed since treatment occurred at time g). Treatment effect heterogeneity by event-time can be highlighted with the following aggregation.

$$\theta_{es}(e) = \sum_{g \in G} \mathbb{1}(g + e \leq T) P(G = g | G + e \leq T) ATT(g, g + e) \tag{5}$$

As an alternative to the simple aggregation of treatment effects, θ_{simple}, I also report an overall treatment effect parameter that averages $\theta_{es}(e)$ over all event times:

$$\theta_{es}^{overall} = \frac{1}{T-1} \sum_{e=0}^{T-2} \theta_{es}(e) \tag{6}$$

Finally, I report the overall group aggregation, which may be preferable as an overall treatment effect aggregation relative to the simple aggregation method, because $\theta_{simple}^{overall}$ systematically places more weight on groups that experience treatment longer. Following Callaway and Sant'Anna (2020), $\theta_{group}(\tilde{g})$ is the average effect of a lead service line replacements among units in group $\tilde{g}$, across all their post-treatment periods. Then, $\theta_{group}^{overall}$ averages these effects together across groups to summarize the overall effect.

$$\theta_{group}(\tilde{g}) = \frac{1}{T - \tilde{g} + 1} \sum_{t=\tilde{g}}^{T} ATT(\tilde{g}, t) \tag{7}$$

$$\theta_{group}^{overall} = \sum_{g \in G} \theta_{group}(g) P(G = g | G + e \leq T) \tag{8}$$

This provides the average effect of participating in the treatment experienced by all units that ever participated.

In addition to studying the effect of LSL replacements on child blood lead levels, I also estimate the effect on housing prices. For this analysis, observations are at the property-year level. Similar to the BLL results, I estimate the group-time average treatment effects, $ATT(g, t)$, where groups comprise all homes that received a replacement in a particular year. I drop all homes that were already treated by the time they were first observed in the data.

not-yet-treated comparison group (invoking Assumption 5 of Callaway and Sant'Anna (2020)), pre-treatment trends are restricted. See Marcus and Sant'Anna (2021) for further discussion.

I aggregate group-time average treatment effects based on either the never-treated or not-yet-treated control group and use the analogous simple, event, and group aggregations from equations 4 to 8. To account for differential trends in housing prices by home type over time, I also use the doubly robust estimator and condition on a variety of home characteristics, including total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade.

4 Results

4.1 Descriptive Analysis and Distributional Impacts

In general, blood lead levels were trending down over this time period from an average of about 4.34 $\mu g/dL$ in 2005 to about 2.18 $\mu g/dL$ in 2016, as seen in Figure 5a. The goal of this paper is to test whether public-side LSL replacements helped contribute to this overall decline and to what extent. Figure 5b shows the trends in average blood lead levels by age of the home. These trends show some suggestive evidence that during the Lead Service Line Replacement Program, from 2007 to 2010, declines in BLLs were largest for children most likely exposed to the program, those who lived in homes built before 1937.

Although blood lead levels were relatively low during this time, especially compared to historical periods, the BLL distribution still showed a long right tail. Table 1 shows the average blood lead level for children in the sample is about 2.9 $\mu g/dL$, with Black children having a higher average at 3.2 $\mu g/dL$. These levels are much higher than the nation-wide average of 0.8 $\mu g/dL$ based on NHANES data from 2011-16 (Egan et al., 2021). Since 2012, the CDC has lowered the blood lead reference value to 3.5 $\mu g/dL$, which is based on the 97.5th percentile of the blood lead values among US children ages 1-5 years. Many children in RI have even higher BLLs. About 13 percent of children had elevated blood lead levels over 5 $\mu g/dL$, and 3 percent had blood lead levels over 10 $\mu g/dL$. Figure 6 shows the distribution of blood lead levels by the year a child's home was built. Children living in homes built before 1937, when LSL were commonly installed, had higher blood lead levels. The solid line shows the distribution of BLL was shifted to the right for these children. On the other hand, children in homes build between 1937 and 1978 or after 1978, when lead paint was banned, had lower blood lead levels. Interestingly, there was little difference in the distribution of blood lead levels between children in homes that may have lead paint and children in homes built after the lead paint ban, which is consistent with existing work showing that lead paint remediation efforts have been effective and may have helped close this gap.

Yet, children living in homes built before 1937 had higher blood lead levels than children living in newer homes. Figure 7 shows the mean blood lead level by year of home age. In panel a, the vertical line denotes the year 1937 and squares show the mean BLL for children living in homes built in each 5-year bin of home age. The line shows the smoothed BLLs over years of home age. Blood lead levels are higher for children living in homes built before 1937. On average, BLLs are about 3.37 and 2.07 $\mu g/dL$ for children in homes built before 1937 and after 1937, respectively. There is a decrease in average BLLs around 1937, suggesting that some of this difference in means may be driven by exposure through lead service lines. Panel b of Figure 7 shows the smoothed blood lead levels by year of home age for tests taken before treatment or for children that were never treated (long dashed line) and for tests taken after treatment (short dashed line). The decline in blood lead levels is concentrated in older homes, which would be expected if the line installations reduce exposure to lead through lead service lines in older homes. These results provide descriptive evidence consistent with the hypothesis that the LSLR Program led to reduced BLLs for children, but we will test this more formally in section 4.2.

Next, I explore the demographic characteristics of the population in Rhode Island that are exposed to lead service lines using data from the 5-year ACS at the block-group level.[17] Table 2 shows detailed demographic, economic, and housing characteristics for neighborhoods with lead exposure and those that were targeted by the LSLR Program. Column 1 shows means for block-groups that do not contain any lead service lines. Columns 2 and 3 include block-groups with at least some lead service lines.

Neighborhoods targeted by the LSLR Program had an older housing stock and higher concentrations of lead service lines. Providence's housing stock is known to be some of the

[17] I define public-side service lines as lead if they are recorded as made of lead as of 2017 or if they were replaced during the LSLR Program from 2007 to 2010.

oldest in the country. Overall, in column 4, about 45 percent of block-groups had a median year of home age before 1939.[18] About 50 percent of neighborhoods with LSL replacements, column 3, had a median year of home age before 1939. Lead service lines are concentrated in these neighborhoods with old housing stock. In column 2, about 21 percent of public-side service lines were made of lead but none were replaced during the LSLR Program, and in column 3, about 41 percent were made of lead and at least some were replaced during the LSLR Program.

Exposure to LSL is not uniformly distributed across the population. As with many other environmental hazards, disadvantaged groups are more likely exposed to lead service lines, as seen in Table 2. Neighborhoods with LSLs are more likely to be renters, to be single headed households, to have a high school education or less, to be unemployed, to receive public assistance, to have a lower household income, to be non-white, and to be Hispanic. This is consistent with Vivier et al. (2011) who show that children in high poverty neighborhoods are almost four times more likely to have elevated BLLs than those in low poverty neighborhoods in Rhode Island.

4.2 Effects on Child Blood Lead Levels

As described in section 3, I follow Callaway and Sant'Anna (2020) to avoid the negative weighting issues inherent in two-way fixed effects estimators in the presence of dynamic treatment effects. Instead, I summarize the effect of lead service line replacements on child blood lead levels by estimating group-time average treatment effects, $ATT(g,t)$, for groups g and time periods t, as described above.

Table 3 shows the overall summary aggregations of the average treatment effects. The sample includes only non-moving households. Columns 1 and 4 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 5 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the group aggregation, $\theta^{overall}_{group}$, from equation 8. The counterfactual is set to the never treated group in columns 1-3 and the not-yet-treated group in columns 4-6. Across all aggregation methods and counterfactual groups in Panel A,

[18] We use 1939 instead of 1937 (when RI stopped installing LSL), because the median year of home age in the ACS is truncated at 1939.

the estimates consistently show a decline in average child blood lead levels of about 0.3-0.4 $\mu g/dL$ following a public-side lead service line replacement. Relative to the mean of 2.89 $\mu g/dL$, the estimates represent a decline of about 12-14 percent.

Panels B and C report results for binary indicators equal to one if a child's blood lead level is over 5 $\mu g/dL$ or over 10 $\mu g/dL$, respectively. The results show replacements led to a significant decline in elevated blood lead levels across all aggregation methods and counterfactual groups. Replacements led to a 5-6 percentage point decline in the probability of having a blood lead level over 5 $\mu g/dL$, or 38-45 percent from the mean. Replacements also had a significant impact on blood led levels over 10 $\mu g/dL$, which declined by about 1-2 percentage points after replacement, or 50-84 percent from the mean.

Table 4 explores heterogeneity in these results by gender, race, and ethnicity. While the coefficients by gender and ethnicity are similar in magnitude, some interesting patterns arise by race. The effects on overall blood lead levels are driven by White children in Panel a. However, Black children have the largest point estimates for reductions in elevated blood lead levels over 5 and over 10 $\mu g/dL$ in Panels b and c, respectively.

Next, I explore heterogeneity in the treatment effects by event-time in Figure 8.[19] The event-study style aggregation, given by equation 5, provides information on trends prior to treatment and the evolution of the effects after treatment. The pre-treatment periods, in orange, show fairly flat and insignificant estimates. The lack of pre-treatment trends gives support for the assumption that blood lead levels would have trended similarly in children with LSL replacements and among children in the counterfactual group, in the absence of treatment. For all three measures, the estimates show a decline in blood lead levels after LSL replacements, which appears to grow somewhat over time. It is not surprising that the decrease in child BLL grows over time, since lead accumulates as it is stored in the body over time, such that it may take time for reductions in BLL to arise.

These results are robust to a number of alternative specifications, as shown in Table 5. Column 1 replicates the main results for each of our BLL measures: average BLL result in panel A, an indicator for over 5 in panel B, and an indicator for over 10 in panel C.[20] First,

[19] While Figure 8 uses the never treated group as the counterfactual, Figure A4 shows the figures using the not-yet-treated group as the counterfactual and finds very similar results.

[20] All results are reported for the simple aggregation and never treated counterfactual group, but are

I explore the robustness of the results to alternative measures of child BLL. Rather than using the yearly average of test results for children with multiple tests in a given year, using the maximum or minimum values within the year produces very similar estimates. Columns 2 and 3 show the estimate when the outcome variables for children with multiple tests in a given year are constructed from either the maximum or minimum BLL, respectively. The magnitude of the effects are slightly larger (smaller) when using the maximum (minimum) values, which is not surprising.

Next, to ensure that the estimates are not driven by outliers of very high blood lead test results, column 4 shows the estimates after dropping the top percentile of test results. Column 5 includes capillary tests in addition to venous tests in the sample. As capillary tests are less accurate than venous tests, it is not surprising that the estimates are somewhat attenuated.

Next, I show the robustness of the results to alternate samples. Column 6 of Table 5 shows estimates based only on the sample of children that were treated during the LSL Replacement program from 2007 to 2010. These treatment cohorts are most likely to contain LSL replacements and, because the utility was required to replace 7 percent of their LSL per year, these replacements are unlikely to be related to household-level changes.[21] In column 7, I show the effects after dropping homes built after 1937.[22] As shown in Figure A3, lead service lines were commonly installed by ProvWater until 1937. Therefore, homes built prior to 1937 were more likely to have had a lead service line prior to the new installation of a line during the study period. The estimates are very similar to the baseline specification, which provides some reassurance that the results are driven by older homes that were likely to have had lead service lines prior to the new installation. In column 8 of Table 5, I use additional information in the data to drop any BLL tests that occur in the same year of treatment, but before the lead service line is replaced. This ensures that the first year of treatment is based only on BLL tests that are taken after treatment begins. Finally, column

robust to using the not yet treated group and other aggregation methods. Table A2, for example, shows similar results for the event study aggregation.

[21]Note that the sample is larger in this estimation because other households with installations outside of the LSLR Program are allowed to act as a counterfactual.

[22]This specification keeps all homes with missing information on year the home was built. As described in the data section, year built data was available only for Providence and Cranston.

9 conditions on the year a child's home was built to account for any differential trends in blood lead levels by age of the house. Across all specifications, the estimates are consistent with the baseline specification and indicate a statistically significant decline in child BLL following a lead service line replacement.

4.3 Effects on Home Sales

To capture the indirect impacts of the program, I focus next on the valuation of public lead service line replacements as measured by changes in home prices. LSL Replacements that occur as part of the LSLR Program are exogenous to the homeowners' decision making process because they are conducted by the water system in response to the regulatory requirement. Alternatively, replacements that occur at other times are likely to be endogenously related to a request by the homeowner. For example, during a home renovation project, a homeowner may choose to replace the private-side of their lead service line and request that the water supply company replace the public-side at the same time. As these replacements are endogeneously related to other home improvements, any price changes would be difficult to interpret because they would simultaneously capture both the effect of the home renovation and the reduced lead exposure from the lead service line. Therefore, I split the sample into replacements that occur during the LSLR Program and those that are not during the LSLR Program, as defined in section 2.

Figure 9 shows the event study aggregation estimates for the probability of a home being sold. Estimates use the never treated control group and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, and initial land assessment, and home grade in order to control for differential trends in home sales during the sample period by housing characteristics. Figure 9a shows that there is little evidence of a change in the probability that a home is sold either before or after the LSL replacement for replacements conducted as part of the LSLR Program. Pre-treatment coefficients in orange and post-treatment coefficients in blue are not statistically different from zero. On the other hand, in Figure 9b, there is a clear increase in the probability of that a home is sold around the time of replacement for replacements performed outside of the LSLR Program. The coefficients in period 0 is positive and statistically significant. Because these replacements may be associated with home remodels and remodels often occur just before or just after a home is sold, it is not surprising that the replacement timing is associated with an increase in the probability of a home sale. These results are consistent with what we would expect to find if replacements are endogenously related to home remodels outside of the LSLR Program. It is reassuring that we do not find a similar increase in the probability of a home sale for replacements performed during the LSLR Program in Figure 9a, as it suggests these replacements are likely exogenous.

Next, I show the results for the effect of LSL replacements during the LSLR Program on home prices. If home buyers value the LSL replacements, we would expect the home price to increase. If LSL replacements are viewed as ineffective, the sales price may not change. If home buyers view the LSL replacements as harmful, potentially increasing lead exposure due to only partial replacements, the change in home price may even be negative. The outcome variable is the log of the sales price, as described in section 2. Estimates use the never treated control group and include year and parcel fixed effects. The doubly robust estimator conditions on a variety of housing characteristics in order to control for differential trends in home sales during the sample period by housing characteristics. Figure 10 shows that after LSL replacement, there is an increase in the price, suggesting that homeowners value the replacements. There is little evidence of pre-trends in the periods before replacement, as shown by flat and insignificant pre-treatment coefficients in orange.

Table 6 reports the overall summary aggregations of the average treatment effects from replacements made during the LSLR program. The outcome is the probability of any home sale, in panel a, and the log of the sale price, in panel b. Columns 1 and 4 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 5 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the group aggregation, $\theta^{overall}_{group}$, from equation 8. The counterfactual is set to the never-treated group in columns 1-3 and the not-yet-treated group in columns 4-6. Consistent withe the results from the event study figures, there is no effect of LSL replacement on the probability of a home being sold for replacements conducted as part of the LSLR Program. Across all aggregations and counterfactual groups the coefficients in panel a are small and statistically insignificant. However, panel b shows that LSL replacements are associated with a 7-8 percentage increase in the price of a home.

This effect is robust to various aggregations and counterfactual groups, as shown across columns in Table 6. In Table A3 we show these results are robust to alternative specifications, such as excluding outliers in home sale price and clustering at the block level. Column 6 of Table A3 also shows there is no effect of LSL replacement on the probability of foreclosure.

The magnitude of this effect is reasonable relative to the existing literature, which has documented even larger effects on housing prices for other lead hazards. Christensen et al. (2022) find a 25-34 percent reduction in the average home value in Flint, MI since the lead crisis, Billings and Schnepel (2017) find that lead paint remediation increases home values by 32 percent, and Gazze (2021) find that state mandates requiring the mitigation of lead hazards in old homes decreases the price of those homes by about 7 percent.[23]

4.4 Behavioral Responses

While the housing sales data is useful in measuring the value that home buyers place on a public lead service line replacement, it is not informative about non-homeowners. In Providence, the proportion of renters is high in neighborhoods with many lead service lines. Table 2 reports that over half of houses are rented in census block groups with at least some lead service lines. Renters are an especially important group to consider as they tend to be lower income and are more likely to be minorities. Importantly, renters are reliant on their landlords to make any home improvements, such as replacing private-side lead service lines. Landlords may have little incentive to make such costly investments.

LSL replacements may impact renters through two different channels: rental prices and information. Although I do not observe rental price data, it is possible that rental prices increase after LSL replacement in a similar to way to home prices. This could increase the probably of moving for low income renters. In addition, replacements may bring new information to renters about the presence of lead in the private-side portion of the service line that is owned by the homeowner and is not replaced by the water utility.

[23]Theising (2019) find an increase of 3-4 percent for mandated private-side lead service line replacements in Madison, WI. Unlike in Madison, homeowners in Providence did not have to pay for these public LSL replacements, thus the changes in home values I observe in this setting are more likely to represent homeowners' valuation of the reduced risk of lead exposure.

While landlords are required to inform renters of any known lead sources, there are no requirements to determine whether a home has a lead service line if it is unknown to the landlord. In practice, many times the service line material is only suspected to be lead based on the age of the home. In this case, when public-side lead service line replacements are conducted, they can check the material of the private side. In addition, ProvWater conducted a variety of tap water sampling tests for lead around the time of replacement and the results were shared with residents. Therefore, lead service line replacements may have provided new information to both homeowners and especially renters that their service line was made of lead. If this is the case, we would expect renters to move to homes with fewer lead hazards, such as newer homes.

Both channels may increase the probability for families to move away from these homes. We use a child's location at each blood test to look at the moving behavior of families after public LSL replacement. Unlike home sales, this measure will capture moves by renters as well as owners.

Figure 11a shows the event study aggregation estimates. The outcome variable is equal to one if a child has ever moved from their first observed residential location. The pre-treatment coefficients in orange are statistically insignificant, suggesting there is little evidence of differential moving behavior prior to a LSL replacement. After replacement, the blue coefficients show an increase in the probability that a child has ever been observed at a new residential location. Panel A of Table 7 shows the effect of lead service line replacements on the probability of moving across various aggregation methods and control groups. The estimates consistently show a statistically significant increase in moving of about 8-9 percent. Because there is no detectable increase in the probability a home is sold in Table 6, this moving behavior is likely driven by renters.

Next, I explore whether these children are more or less likely to move to a newer home. Homes built after 1937 are less likely to have lead service lines and homes built after 1978 are less likely to have lead paint. Figure 11b and Panel B of Table 7 show there is a significant increase in the probability of living in a home built after 1937 of about 8-9 percentage points. Figure 11c and Panel C of Table 7 show there is a significant increase in the probability of living in a home built after 1978 of about 3 percentage points. The estimates are consistent across aggregation methods and control groups reported in columns 1-6. These results suggest that the LSL replacements may act as an information channel to renters that increases their probability of moving to a newer home to avoid lead exposure.

Finally, I show the effect of LSL replacements on the probability of testing in Figure 11d and Panel D of Table 7. The outcome is equal to one if a child has any blood lead test at a given age. The sample includes movers and defines LSL replacement timing based on the child's first observed location. Figure 11d shows a decline in the probability of testing after a child's LSL is replaced. Panel D shows that after LSL replacements, a child is about 5 percentage points less likely have a lead test. The estimate is consistent across aggregation methods and control groups reported in columns 1-6.

Rhode Island's testing requirements indicate that children over 36 months old may be asked risk assessment questions to determine whether they must receive a blood lead test. Children living at homes built before 1978 with peeling or chipping paint are required to have a lead test. Given that Panels B and C show children are moving away from older homes, it is not surprising that the frequency of testing declines slightly as children living at new homes are not necessarily required to have a lead test.

5 Discussion & Conclusion

This paper provides evidence of the effect of partial public-side lead service line replacements on child blood lead levels and housing prices. Replacement of public-side lead service lines, conducted as part of Providence Water's LSLR Program, significantly reduced child blood lead levels by about 0.4 $\mu g/dL$, or 13 percent from the mean. Considering that public-side replacements may not have entirely eliminated exposure to lead through drinking water if private-side lead lines or lead interior plumbing remained, this is likely an underestimate of the contribution of drinking water to children's overall lead exposure. Nevertheless, it is in line with the EPA's estimates that drinking water can make up 20 percent or more of a person's total exposure to lead.[24]

This represents a sizable decline in child blood lead levels. Relative to the overall decline

[24] https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

in child blood lead levels during the study period, the 0.4 $\mu g/dL$ decline accounts for about 19 percent. Relative to the gap in average child blood lead levels for children living in homes built before and after 1937, when LSL were no longer installed in Rhode Island, the effect of LSL replacement is about 31 percent. Based on existing literature, a 0.4 unit decline in BLL is expected to reduce the probability of school suspension by 2.4% and juvenile detention by 23% (Aizer and Currie, 2019), and reduce the probability of being substantially below proficient in reading and math by 3.2% and 2%, respectively (Aizer et al., 2018).

I also find that LSLRs increase home values by about 7-8 percent, suggesting that homeowners value the public-side LSL replacements more than the cost. Using the average home sales price of $238,000, this suggests a valuation of about $16,000 to $19,000 per public-side LSLR, which is about three to four times as large as the average cost of a public-side replacement, $4,800 (Providence Water, 2021). The Infrastructure Investment and Jobs Act of 2021 recently dedicated $15 billion to fully replace lead service lines throughout the US. Replacing the entire LSL is likely to benefit homeowners even more than the partial replacements studied here. Yet, if we take a conservative estimate of the increase in home value of $16,000, replacing the 6 to 10 million remaining lead service lines could generate benefits of $96-$160 billion.

While homeowners value these replacements, these estimates do not consider the impact of LSLR on renters. Renters are an especially important group in this context, as they are disproportionately exposed to lead service lines, but are reliant on landlords to pay for private-side replacements. In practice, landlords are only required to inform renters of known lead hazards. As the private-side composition of service lines is commonly uncertain, renters may have been unaware of the presence of LSLs and replacements may have provided new information about the presence of public and private lead service lines at their residence. Although there is no change in the probability of a home selling, I show that children are about 8 percent more likely to have moved to a new residential address after LSL replacement. Consistent with the idea that these families are trying to reduce lead exposure, these children are more likely to live in newer homes with fewer lead hazards after replacement.

These findings show that even partial lead service line replacements can reduce child blood lead levels and show that lead service lines are an important contributor to overall child blood lead levels. As no level of lead exposure is considered safe, we must address lead exposure through drinking water in addition to other channels of exposure, such as through lead paint. The Infrastructure Investment and Jobs Act takes an important step in this direction by funding full lead service line replacements. As current replacement efforts are focused on full replacement of both public and private lead service lines, we expect the reduction in child blood lead levels may be even larger. Providing funding for full lead service line replacements will also help protect renters and other disadvantaged groups that do not own or cannot afford to replace private-side lead service lines, yet are disproportionately exposed to lead service lines.

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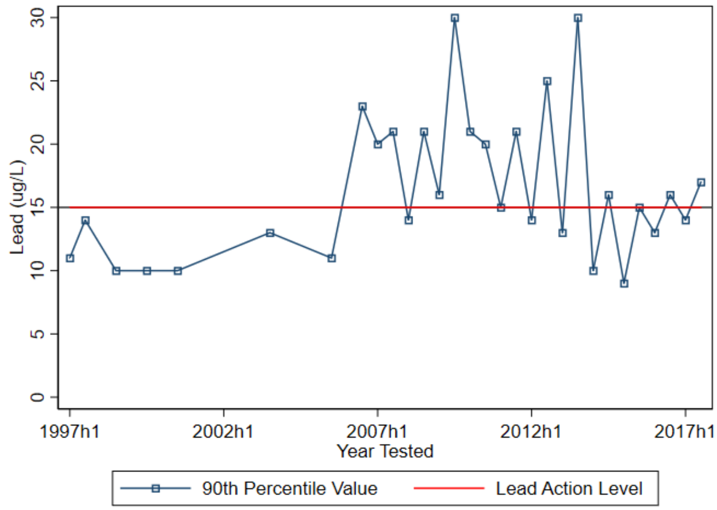
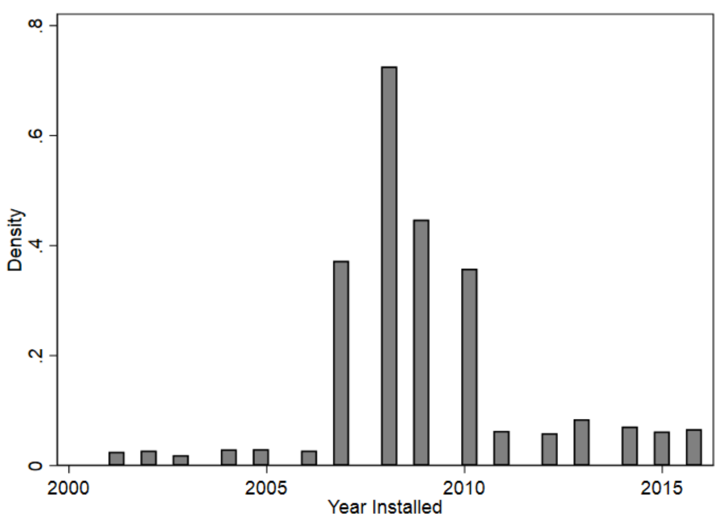
Figures

Figure 1: Providence Water LCR Compliance History



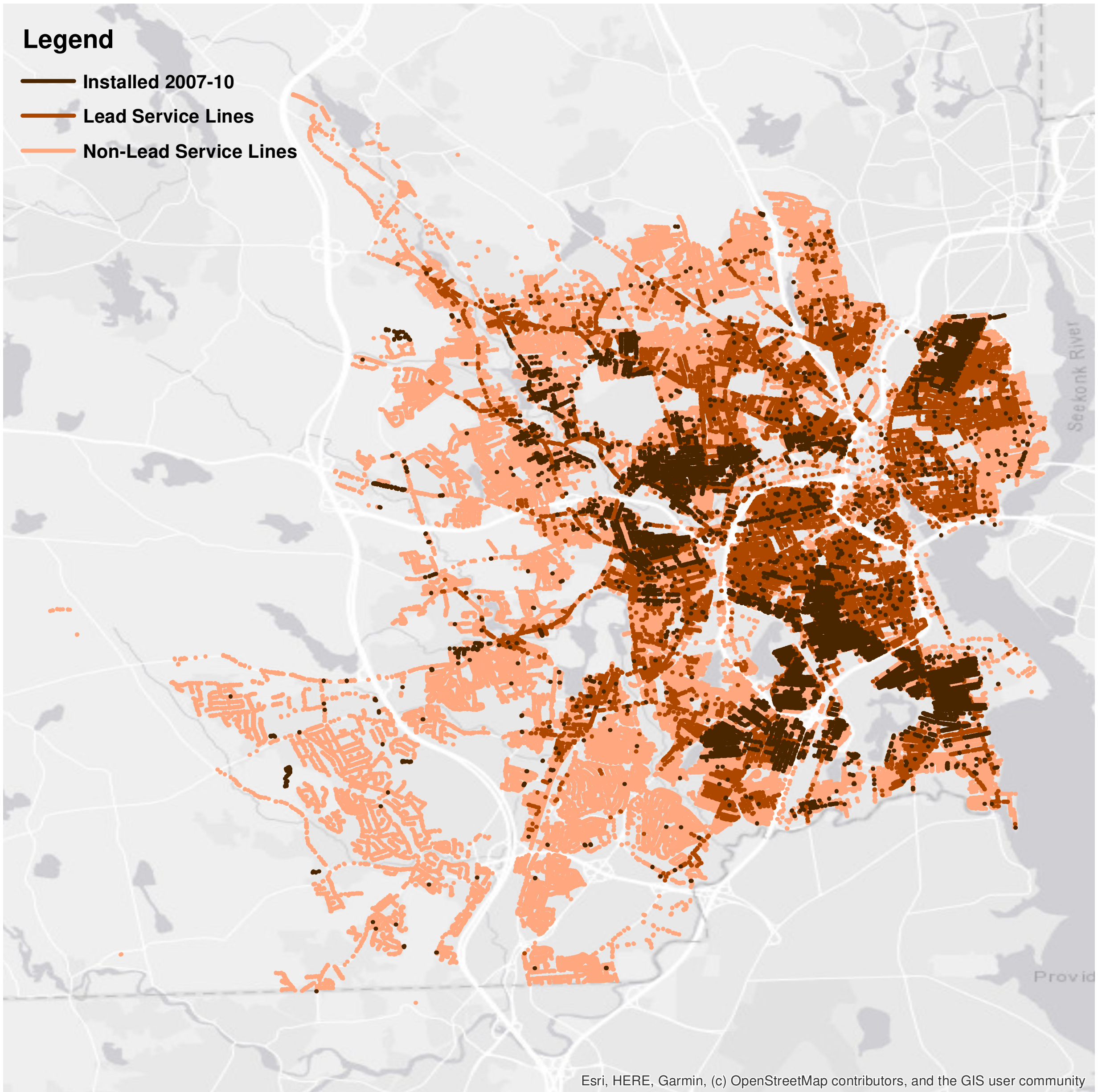
Notes: EPA's Lead and Copper Rule establishes a lead action level of 15 $\mu g/L$, shown by the red line. As approved by the Rhode Island Department of Health (RIDOH), the sampling frequency has changed over time.

Figure 2: Year service lines installed among old homes



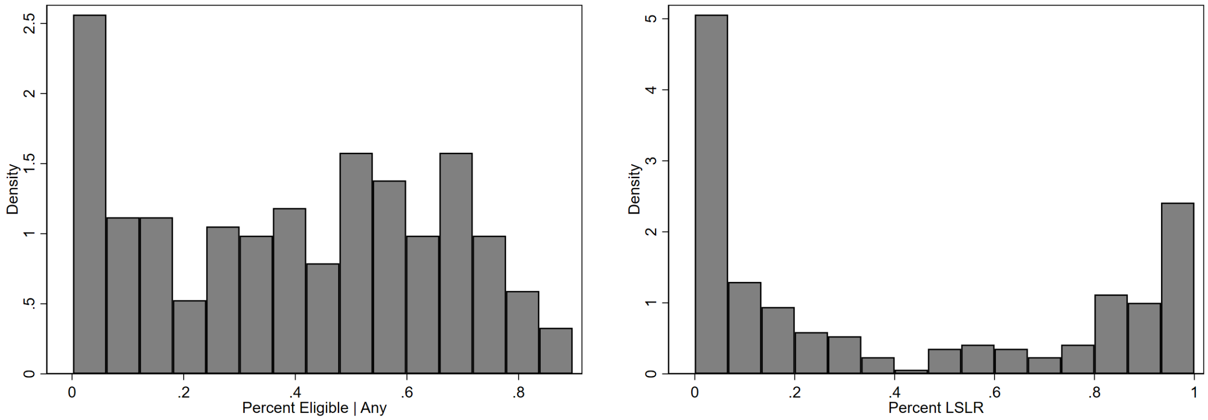
Notes: Figure shows the histogram of service lines installed after 2000 by year of installation among homes built before 1937. The dramatic rise in installations between 2007 and 2010 corresponds to the lead service line replacement program. Lead service lines were commonly installed prior to 1937, making homes built before 1937 more likely to have lead service lines. While data on year homes were built is not available for the whole sample, the figure looks remarkably similar in the full sample, without restricting to homes built prior to 1937, which is shown in Appendix Figure A2.

Figure 3: Lead and Non-lead Service Lines



Notes: Figure shows the location of ProvWater public service lines in Rhode Island. Non-lead service lines are shown in light peach, lead service lines that had not yet been replaced by 2017 are shown in medium brown, and service lines that were installed during the Lead Service Line Replacement program (between 2007 and 2010) are shown in dark brown.

Figure 4: Distribution of Treatment at Block Group Level

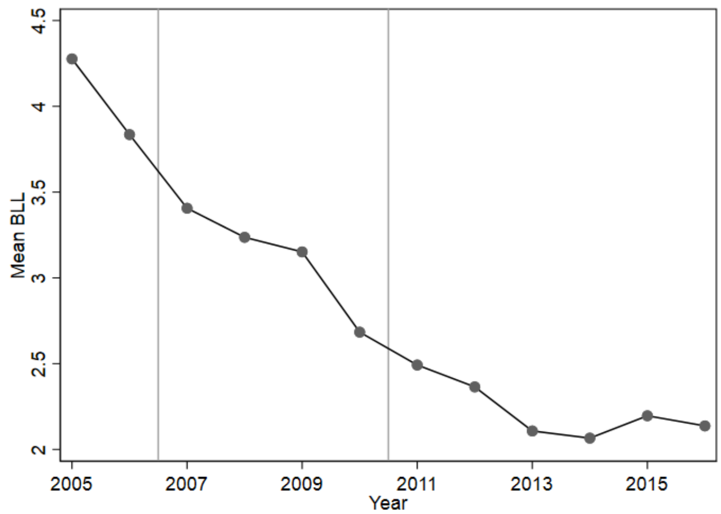


(a) Percent Lines Eligible (Lead) if Any

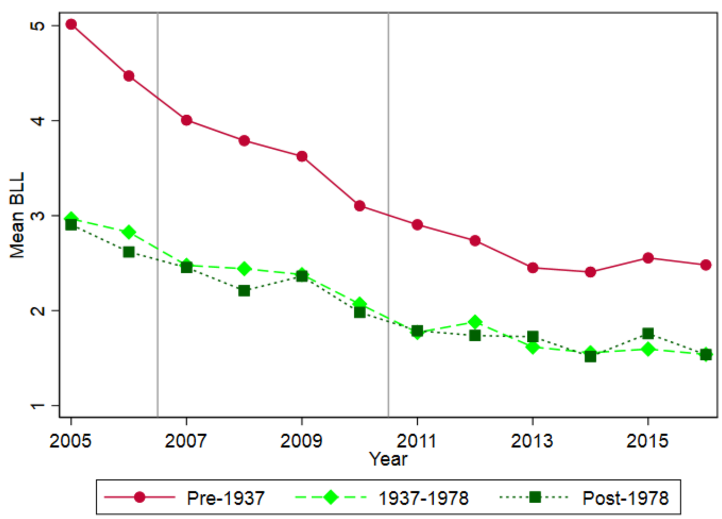
(b) Percent of Eligible Lines Replaced

Notes: Observations are at the block group level. Panel a shows the distribution of the percent of total service lines that were "eligible" for replacement, conditional on having any eligible lines. Eligible lines are defined as service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Panel b shows the distribution of the percent of total "eligible" lines that were replaced during the LSLR Program.

Figure 5: Trend in Child BLLs over Time



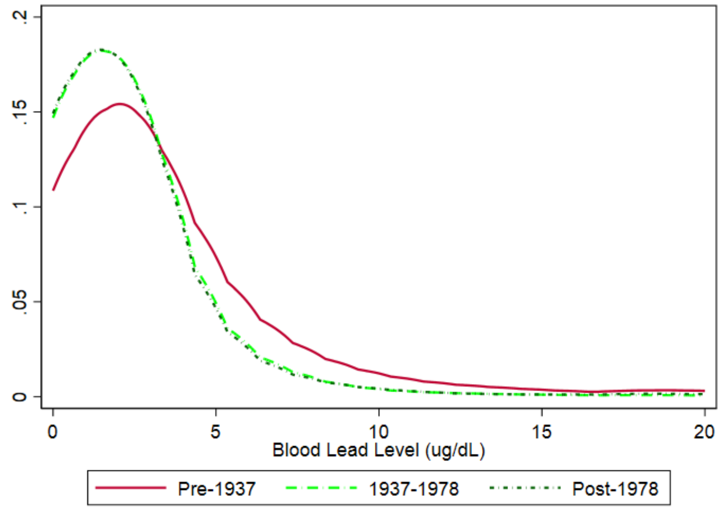
(a) Mean BLL



(b) Mean BLL by Home Age

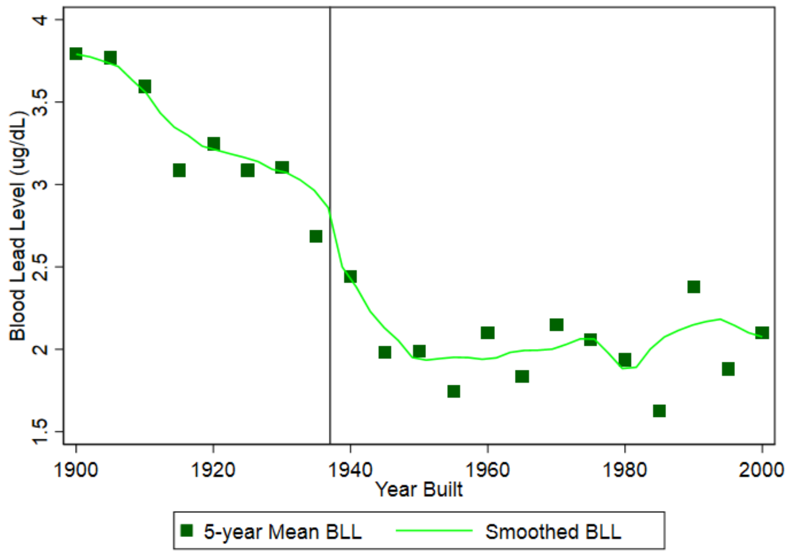
Notes: Vertical lines denote the start and end of the Lead Service Line Replacement Program in Providence, RI. Panel a shows the average blood lead levels for all children tested from 2005 to 2016 in Rhode Island. Panel b shows the average blood lead levels by age of home construction: built before 1937, built from 1937 to 1978, and built after 1978.

Figure 6: Distribution of Child BLLs by Home Age

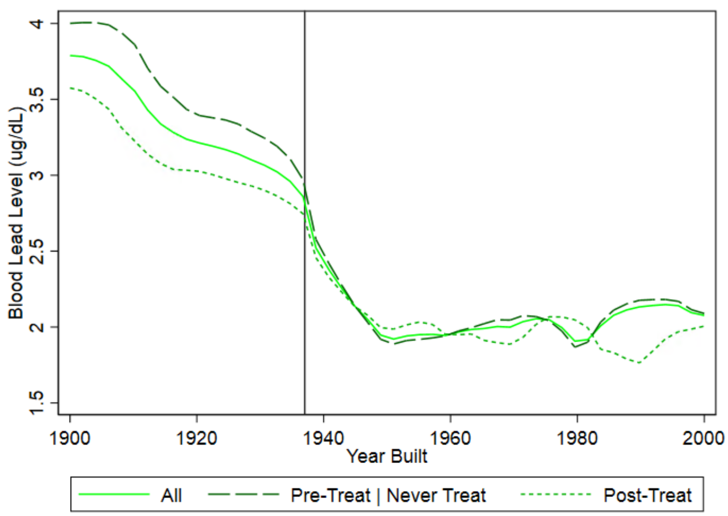


Notes: The figure shows the distribution of blood lead levels for children in homes built before 1937 (solid line), between 1937 and 1978 (dashed line), and after 1978 (dotted line). Lead service lines were primarily installed before 1937 and lead paint was banned for residential use in 1978. The figure focuses on BLLs below 20 $/mug/dL$, but a small fraction are even higher, as shown in Table 1.

Figure 7: Child BLL by Year Home Built



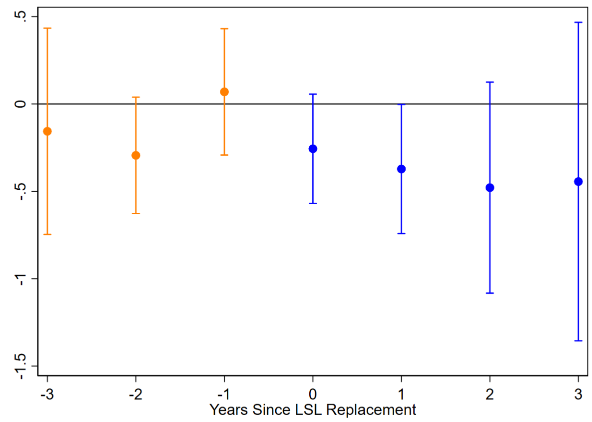
(a) BLL By Year Built



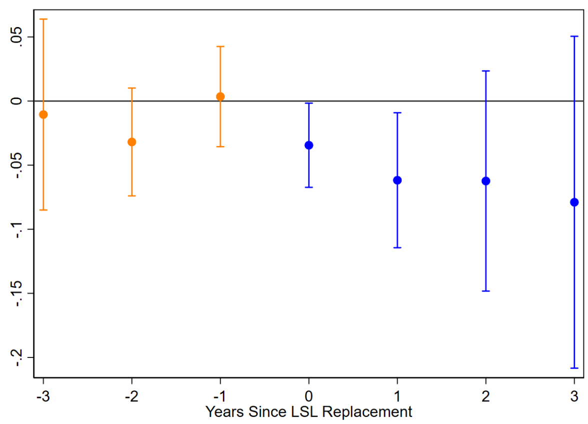
(b) BLL By Year Built, Pre/Post

Notes: Panel a shows the mean blood lead level by year of home construction from 1900 to 2000. Squares represent the mean BLL for each 5-year bin. Binned endpoints include homes built 1900 or earlier and 2000 or later. The line shows the smoothed relationship between blood lead levels and age of the house using 'lpoly'. The vertical line denotes 1937, the year in which lead service lines were no longer installed. Panel b shows the smoothed relationship between blood lead levels and the age of the house using 'lpoly'. The solid line represents all observations, the long dashed line represents blood lead tests of children before line replacement or who were never treated, and the short dashed line represents blood lead tests of children after line replacement.

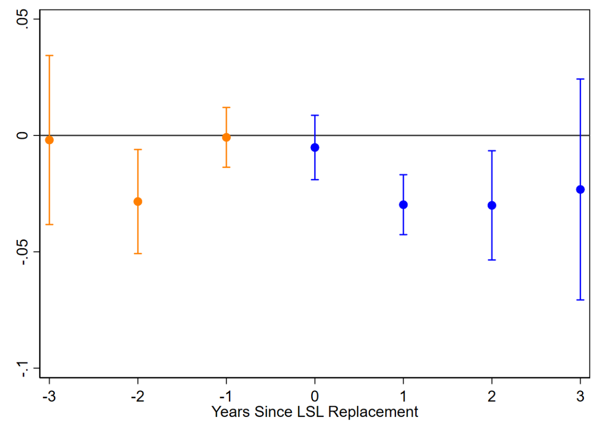
Figure 8: Effect of LSLR on Child BLL



(a) BLL Test Result



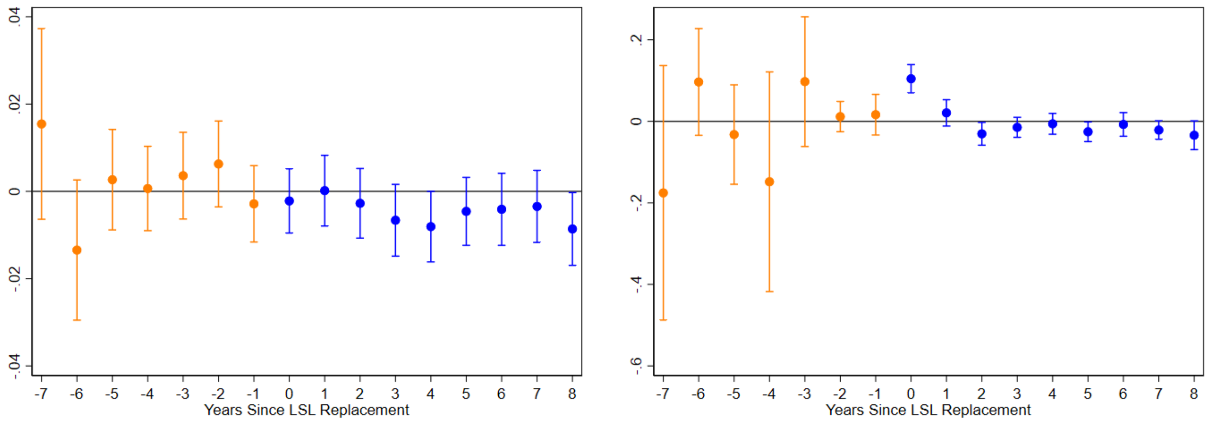
(b) BLL Over 5



(c) BLL Over 10

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (c) show results for the BLL test result, an indicator for BLL over 5 $\mu g/dL$ and an indicator for BLL over 10 $\mu g/dL$, respectively.

Figure 9: Effect of LSLR on Probability of Home Sale

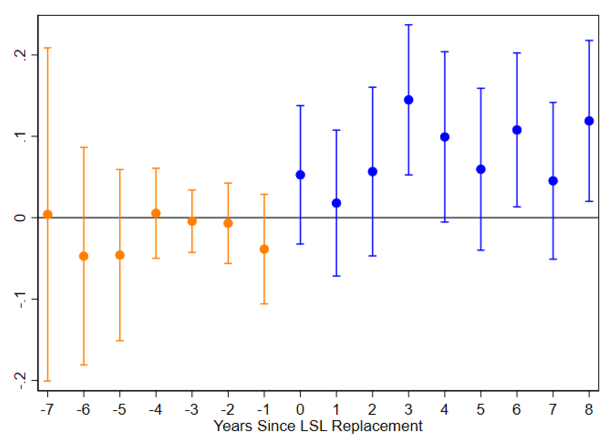


(a) LSLR Program

(b) Not LSLR Program

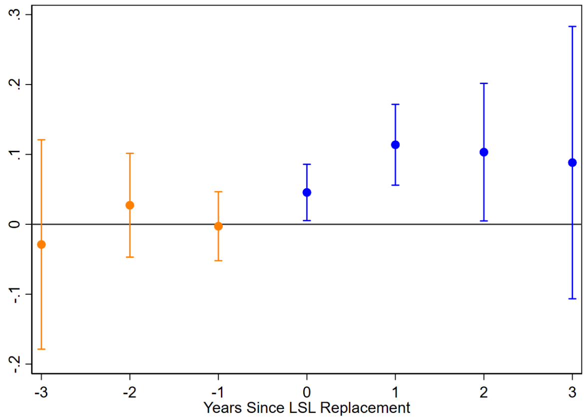
Notes: Event study aggregation estimates reported for LSL replacements made during the LSLR Program (panel a) and not during the LSLR Program (panel b). The x-axis reports years since the service line was replaced. The outcome is equal to one if the home sold in each year. Post-treatment estimates in blue are relative to period -1. Pre-treatment estimates in orange are relative to the previous period. Estimates use the "never treated" control group and include year and parcel fixed effects. Anticipation is zero for replacements during the LSLR program and one for other replacements. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals are clustered at the parcel level.

Figure 10: Effect of LSLR Program on Home Price

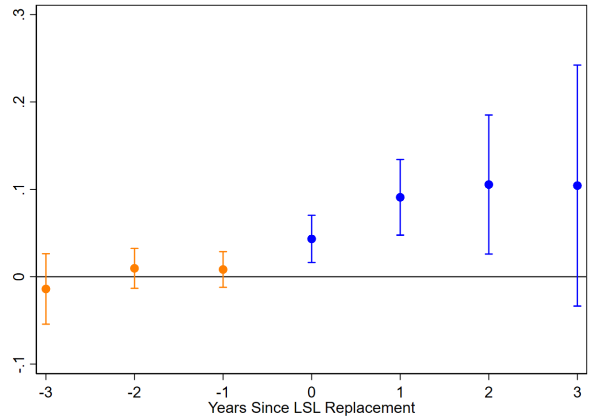


Notes: Event study aggregation estimates reported for LSL replacements made during the LSLR Program. The x-axis reports years since the service line was replaced. The outcome is the log of the sale price. Post-treatment estimates in blue are relative to period -1. Pre-treatment estimates in orange are relative to the previous period. Estimates use the "never treated" control group, have zero anticipation, and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals are clustered at the parcel level.

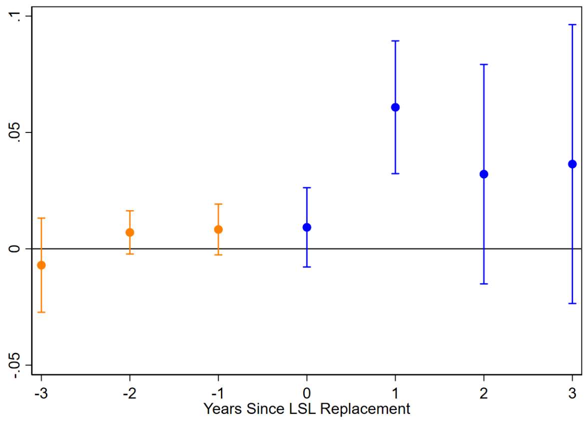
Figure 11: Effect of LSLR on Moving and Testing Behavior



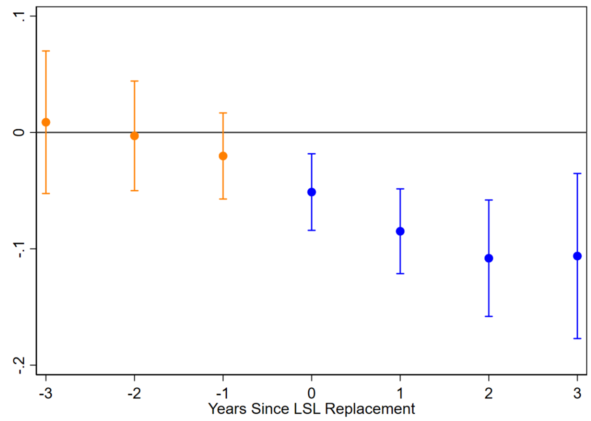
(a) Ever Moved



(b) Live in Post-1937 Home



(c) Live in Post-1978 Home



(d) Any Test

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (d) show results for an indicator equal to one if the child ever moved from the original location, an indicator equal to one if the home was built after 1937, an indicator equal to one if the home was built after 1978, and an indicator equal to one if a child had a BLL test, respectively.

Tables

Table 1: BLL Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
BLL in $\mu g/dL$	14,583	2.886	2.943	0	49
BLL Over 5 $\mu g/dL$	14,583	0.131	0.338	0	1
BLL Over 10 $\mu g/dL$	14,583	0.026	0.160	0	1
Years of Age	14,583	2.273	1.460	0	5
BLL | Male	7,629	2.932	2.957	0	40.5
BLL | Female	6,954	2.837	2.926	0	49
BLL | White	3,940	2.974	2.891	0	35.25
BLL | Black	1,738	3.187	3.165	0	49
BLL | Other Race	6,986	2.751	2.924	0	40.5
BLL | Hispanic	4,453	2.685	2.640	0	40.5
BLL | Non-Hispanic	9,764	3.020	3.080	0	49

Notes: The sample is restricted to non-movers. Observations are at the child-age level. For children with multiple tests per year of age, the mean is reported.

Table 2: Characteristics of Population Exposed to Lead Service Lines and Replacements

	(1)	(2)	(3)	(4)
	No Lead	Lead		Total
		None Replaced	Any Replaced	
Lead Lines (%)	0	0.210	0.411	0.367
Median year built	1964.5	1957.3	1949.0	1950.7
Median built before 1939	0	0.278	0.504	0.452
Average household size	2.315	2.043	2.647	2.582
Houses owned (%)	0.683	0.427	0.495	0.504
Houses mortgaged (%)	0.694	0.733	0.736	0.732
Houses rented (%)	0.317	0.573	0.505	0.496
Vacant (%)	0.0606	0.0921	0.121	0.114
Single Headed HHs (%)	0.243	0.333	0.412	0.394
Non-family HHs (%)	0.360	0.544	0.397	0.404
Single person HHs (%)	0.859	0.829	0.766	0.777
HS Educ or less (%)	0.346	0.371	0.468	0.452
Bachelors Degree (%)	0.215	0.200	0.164	0.170
Masters or Doctorate Degree	0.129	0.189	0.125	0.129
Unemployed (%)	0.0763	0.126	0.130	0.125
Public Assistance(%)	0.00955	0.0352	0.0400	0.0374
Median HH income	62419.6	52563.6	49933.5	51033.7
White (%)	0.902	0.737	0.634	0.661
Black (%)	0.0381	0.0876	0.123	0.114
Other (%)	0.0813	0.192	0.275	0.255
Hispanic (%)	0.0354	0.156	0.278	0.251
Under age 18 (%)	0.179	0.136	0.218	0.210

Notes: Means are reported from the 5-year American Community Survey and observations are at the block group level. Column (1) includes block groups without any lead service lines. Column (2) includes block groups with some lead service lines, but none were replaced during the LSLR Program. Column (3) includes block groups with some lead service lines and some replacements during the LSLR Program. Column (4) shows the full sample of block groups.

Table 3: Effect of Lead Service Line Replacements on Child Blood Lead Levels

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.	*Outcome: BLL*					
After Install	-0.364**	-0.388*	-0.431***	-0.343**	-0.371*	-0.416**
	(0.152)	(0.199)	(0.164)	(0.150)	(0.197)	(0.177)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$					
After Install	-0.054***	-0.059***	-0.053***	-0.051***	-0.057**	-0.050***
	(0.019)	(0.024)	(0.019)	(0.019)	(0.026)	(0.019)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$					
After Install	-0.021***	-0.022**	-0.014*	-0.019***	-0.020**	-0.013*
	(0.007)	(0.009)	(0.007)	(0.007)	(0.009)	(0.007)
Observations	6,375	6,375	6,375	6,375	6,375	6,375
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes
Non-movers	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and condition on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level.

Table 4: Heterogeneity of BLL Results

	(1) Baseline	(2) Male	(3) Female	(4) White	(5) Black	(6) Other	(7) Hisp	(8) Non-Hisp
Panel A.	*Outcome: BLL*							
After Install	-0.364**	-0.364	-0.378*	-0.912***	-0.759	-0.004	-0.285	-0.354
	(0.152)	(0.242)	(0.214)	(0.316)	(0.523)	(0.182)	(0.231)	(0.267)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$							
After Install	-0.054***	-0.051*	-0.054**	-0.041	-0.077	-0.038	-0.052*	-0.041
	(0.019)	(0.030)	(0.026)	(0.044)	(0.052)	(0.025)	(0.029)	(0.031)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$							
After Install	-0.021***	-0.019*	-0.021**	-0.030**	-0.047*	-0.021**	-0.016*	-0.022**
	(0.007)	(0.012)	(0.010)	(0.014)	(0.027)	(0.009)	(0.009)	(0.010)
Observations	6,375	3,336	3,039	1,785	791	2,901	1,742	4,463
Aggregation	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple
Control Group	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Notes: Results show the overall summary aggregations of the average treatment effects based on simple aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Column 1 replicates the baseline results, and columns 2 to 8 show sub-samples by gender, race, and ethnicity.

Table 5: Robustness of BLL Results to Alternate Specifications

	(1) Baseline	(2) Max	(3) Min	(4) No Outliers	(5) With Capillary	(6) 2007-10	(7) Drop 1937+	(8) Fix After	(9) Year Built Control
Panel A.	*Outcome: BLL*								
After Install	-0.364**	-0.477***	-0.256*	-0.295**	-0.281**	-0.453**	-0.329**	-0.348**	-0.380**
	(0.152)	(0.164)	(0.147)	(0.147)	(0.142)	(0.201)	(0.162)	(0.160)	(0.155)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$								
After Install	-0.054***	-0.061***	-0.047**	-0.053***	-0.047***	-0.054**	-0.050**	-0.058***	-0.056***
	(0.019)	(0.020)	(0.019)	(0.019)	(0.019)	(0.026)	(0.020)	(0.022)	(0.019)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$								
After Install	-0.021***	-0.027***	-0.017***	-0.019***	-0.017**	-0.023***	-0.020***	-0.014*	-0.022***
	(0.007)	(0.008)	(0.006)	(0.006)	(0.008)	(0.007)	(0.007)	(0.009)	(0.007)
Observations	6,375	6,375	6,375	6,371	6,955	15,859	5,921	6,357	6,375
Aggregation	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple
Control Group	Never	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects based on simple aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Columns 2-3 use the maximum and minimum BLL values for children with multiple tests per year, respectively. Column 4 excludes the top 1% of BLL tests. Column 5 includes capillary tests. Column 6 uses only treatment cohorts with lines installed during the LSLR Program (2007-2010). Column 7 excludes homes built after 1937 that are less likely to have had lead service lines. Column 8 excludes BLL tests taken in the same year as treatment but before the line was replaced. Column 9 also conditions on the year a child's home was built.

Table 6: Effects on Home Sales

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.	*Outcome:* $\mathbb{1}$*[Any Home Sale]*					
After Install	-0.0045	-0.0045	-0.0043	-0.0044	-0.0044	-0.0043
	(0.0032)	(0.0030)	(0.0031)	(0.0032)	(0.0030)	(0.0031)
Observations	13,767	13,767	13,767	13,767	13,767	13,767
Panel B.	*Outcome: Log(Sale Price)*					
After Install	0.067**	0.078**	0.075**	0.070**	0.081**	0.077**
	(0.031)	(0.034)	(0.036)	(0.032)	(0.035)	(0.036)
Observations	7,258	7,258	7,258	7,258	7,258	7,258
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Controls	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta_{simple}^{overall}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta_{es}^{overall}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Sample includes LSL replacements made during the LSLR Program at old homes. The outcome is any sale in panel a and the log of home price in panel b. Estimates have zero anticipation and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals and clustered at the parcel level are reported in parentheses.

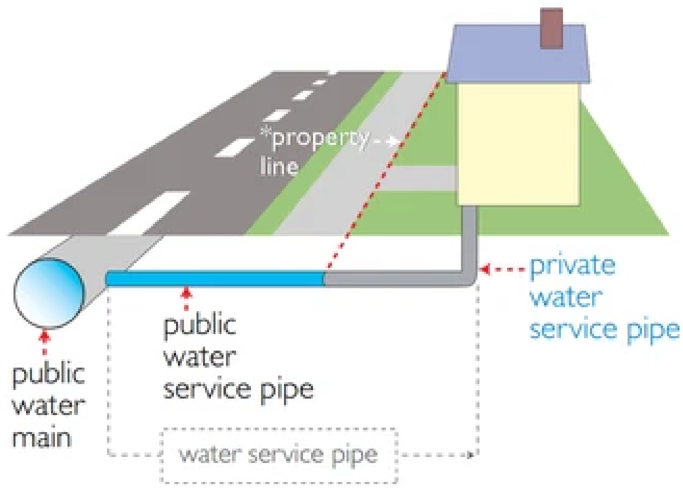
Table 7: Effect of Lead Service Line Replacements on Moving and Testing Behavior

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.			*Outcome:* $\mathbb{1}[Ever\ Moved]$			
After Install	0.082***	0.088*	0.079***	0.082***	0.088**	0.079***
	(0.033)	(0.045)	(0.024)	(0.032)	(0.045)	(0.025)
Observations	12,613	12,613	12,613	12,613	12,613	12,613
Panel B.			*Outcome:* $\mathbb{1}[Live\ in\ Post-1937\ Home]$			
After Install	0.089***	0.086***	0.074***	0.089***	0.086***	0.074***
	(0.018)	(0.027)	(0.016)	(0.019)	(0.025)	(0.015)
Observations	16,079	16,079	16,079	16,079	16,079	16,079
Panel C.			*Outcome:* $\mathbb{1}[Live\ in\ Post-1978\ Home]$			
After Install	0.034***	0.035***	0.031***	0.033***	0.034***	0.031***
	(0.011)	(0.012)	(0.010)	(0.010)	(0.011)	(0.010)
Observations	16,079	16,079	16,079	16,079	16,079	16,079
Panel D.			*Outcome:* $\mathbb{1}[Any\ Test]$			
After Install	-0.049***	-0.051***	-0.049***	-0.046***	-0.048***	-0.047***
	(0.010)	(0.011)	(0.009)	(0.010)	(0.010)	(0.009)
Observations	25,267	25,267	25,267	25,267	25,267	25,267
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. Estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Treatment timing is based on the child's first observed location. The outcome in panel a is an indicator equal to one if a child ever moved from their initial location. Observations are set to missing in the first year a child is observed. The outcomes in panels b and c are indicators equal to one if the child lives in a home built after 1937 and 1978, respectively. The outcome in panel d is an indicator for whether a child had any BLL test at each age from 0 to 5.

Appendix

Figure A1: Service Lines: Public and Private Portions



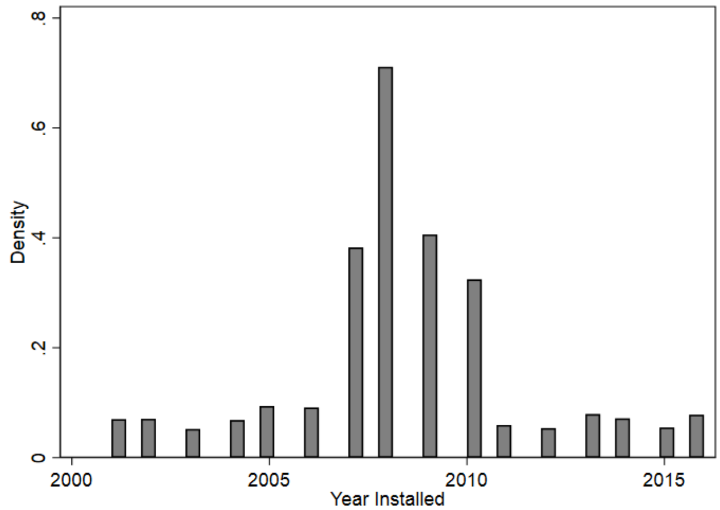
Notes: Figure shows an example of a service line that connects homes to water mains. The privately owned portion connects from the home to the property line and the publicly owned portion connects from the property line to the water main.

Table A1: Rhode Island Blood Lead Screening

Panel A. Universal Blood Lead Screening
Screen all children from nine months to six years of age (9 to 72 months) for lead poisoning at least once annually. Children age 9-36 months: –Screen once between 9-15 months of age, and –Screen again 12 months later, between 21 and 36 months of age. Children age 36-72 months: –If a child was screened at least twice prior to 36 months of age, and any test was greater than or equal to 5 $\mu g/dL$, continue to order a blood lead test at least once a year until the child is six years old. –If a child was screened at least twice prior to 36 months of age, and ALL tests were lower than 5 $\mu g/dL$, the Risk Assessment Questions below can be used instead of a blood lead test to screen for lead. –If a child was NOT screened at least twice prior to 36 months of age, order a blood lead test. If the blood lead level is higher than or equal to 5 $\mu g/dL$, follow the recommended actions and screen annually. If the blood lead level is lower than 5 $\mu g/dL$, the Risk Assessment Questions below can be used instead of a blood lead test, to screen for lead, in the future.
Panel B. Risk Assessment Questions
If the answer to ANY of these questions is YES, order a blood lead test. If the answer to ALL of these questions is NO, blood lead testing can be discontinued, but the Risk Assessment Questions should be asked annually until the child is six years old. 1. Does your child live in or regularly visit a house built before 1978 with peeling or chipping paint (daycare center, pre- school, home of babysitter, friend, or relative)? 2. Does your child live in or regularly visit a house built before 1978 that has been renovated or remodeled in the last six months? 3. Does your child have a brother, sister, housemate, or playmate who has or did have lead poisoning? 4. Does your child live near an active smelter, battery recycling plant, or other industry likely to release lead? 5. Does your child live with an adult whose job (i.e., construction, painting) or hobby (i.e. pottery, stained glass, furniture refinishing, automotive bodywork, or boat refinishing) involves exposure to lead?

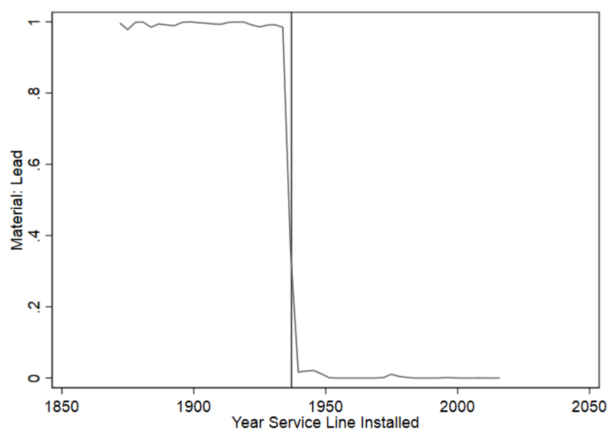
Source: Rhode Island Department of Health, Childhood Lead Poisoning Prevention Program Referral Intervention Process (2019).

Figure A2: Year service lines installed, full sample



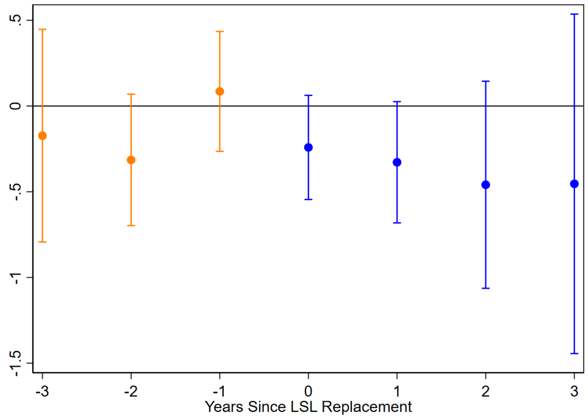
Notes: Figure shows the histogram of service lines installed after 2000 by year of installation for the full sample. The dramatic rise in installations between 2007 and 2010 corresponds to the lead service line replacement program.

Figure A3: Service line material by year installed

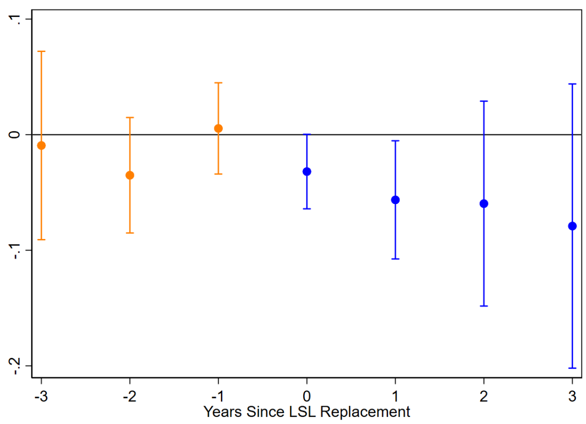


Notes: Figure shows the proportion of newly installed service lines constructed from lead by year of service line installation based on service line installation data from ProvWater. The vertical line denotes year 1937, after which lead service lines were no longer regularly installed.

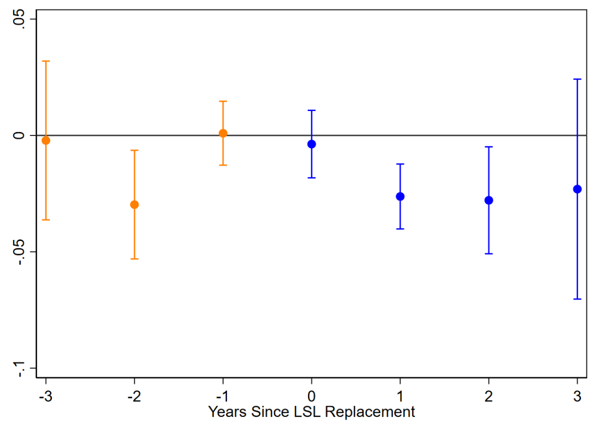
Figure A4: Effect of LSLR on Child BLL, not yet treated



(a) BLL Test Result



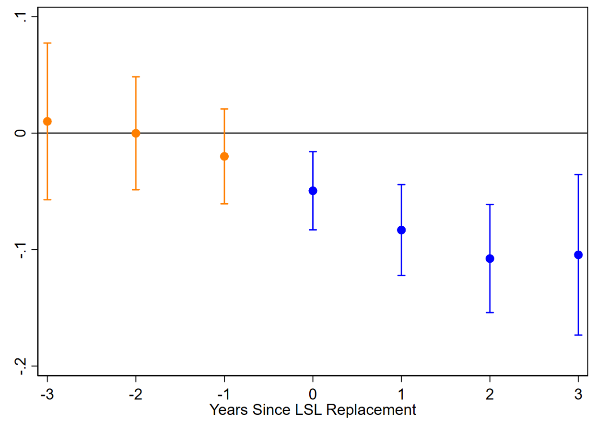
(b) BLL Over 5



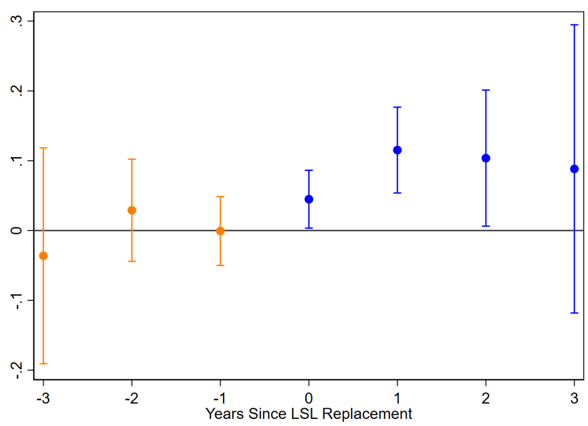
(c) BLL Over 10

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is not yet treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (c) show results for the BLL test result, an indicator for BLL over 5 $\mu g/dL$ and an indicator for BLL over 10 $\mu g/dL$, respectively.

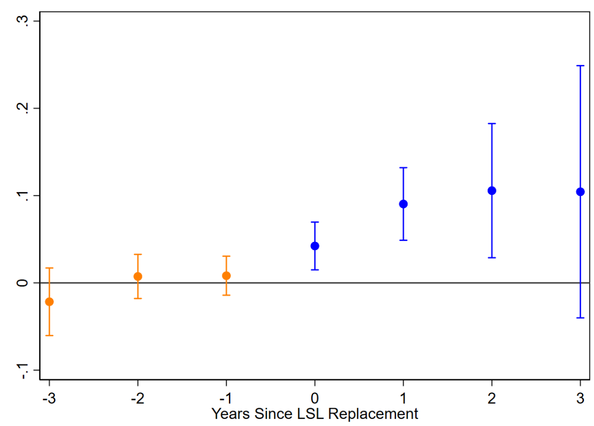
Figure A5: Effect of LSLR on Testing and Avoidance, not yet treated



(a) Any Test



(b) Ever Moved



(c) Live in Post-1937 Home

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is not yet treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (c) show results for an indicator equal to one if a child had a BLL test, an indicator equal to one if the child ever moved from the original location, and an indicator equal to one if the home was built after 1937, respectively.

Table A2: Robustness of BLL results to alternate specifications, event aggregation

	(1) Baseline	(2) Max	(3) Min	(4) No Outliers	(5) With Capillary	(6) 2007-10	(7) Drop 1937+	(8) Fix After	(9) Year Built Control
Panel A.	*Outcome: BLL*								
After Install	-0.388*	-0.506**	-0.274	-0.329*	-0.321*	-0.487*	-0.329**	-0.368*	-0.406**
	(0.199)	(0.206)	(0.191)	(0.186)	(0.172)	(0.254)	(0.162)	(0.213)	(0.199)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$								
After Install	-0.059***	-0.064***	-0.049**	-0.058**	-0.054**	-0.060*	-0.055**	-0.059**	-0.061**
	(0.024)	(0.024)	(0.024)	(0.025)	(0.023)	(0.032)	(0.026)	(0.024)	(0.025)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$								
After Install	-0.022**	-0.028***	-0.017**	-0.020**	-0.017*	-0.023***	-0.021**	-0.016*	-0.023***
	(0.009)	(0.009)	(0.008)	(0.008)	(0.010)	(0.009)	(0.009)	(0.010)	(0.008)
Observations	6,375	6,375	6,375	6,371	6,955	15,859	5,921	6,357	6,375
Aggregation	Event	Event	Event	Event	Event	Event	Event	Event	Event
Control Group	Never	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects based on event study aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Columns 2-3 use the maximum and minimum BLL values for children with multiple tests per year, respectively. Column 4 excludes the top 1% of BLL tests. Column 5 includes capillary tests. Column 6 uses only treatment cohorts with lines installed during the LSLR Program (2007-2010). Column 7 excludes homes built after 1937 that are less likely to have had lead service lines. Column 8 excludes BLL tests taken in the same year as treatment but before the line was replaced. Column 9 also conditions on the year a child's home was built.

Table A3: Robustness of Home Price Results to Alternate Specifications

	(1) Baseline	(2) > $10k	(3) < $1m	(4) > $10k & < $1m	(5) Cluster Block	(6) Any Foreclosure
Panel A.	*Aggregation: Simple*					
After Install	0.066**	0.062*	0.076**	0.072**	0.066*	-0.002
	(0.031)	(0.030)	(0.031)	(0.031)	(0.039)	(0.002)
Observations	7,257	7,251	7,205	7,199	7,257	13,768
Panel B.	*Aggregation: Event*					
After Install	0.077**	0.073**	0.088**	0.083***	0.077*	-0.002
	(0.034)	(0.032)	(0.035)	(0.031)	(0.041)	(0.002)
Observations	7,257	7,251	7,205	7,199	7,257	13,768
Control Group	Never	Never	Never	Never	Never	Never
Controls	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Panel A shows the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Panel B shows the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. The counterfactual is the nevertreated group. Column 1 replicates the baseline results. Columns 2-4 limit the sample to sales prices above $10,000, below $1 million, and with both restrictions. Column 5 clusters the standard errors at the block level. Column 6 shows that there is no change in the probably of foreclosure after replacement. Sample includes LSL replacements made during the LSLR Program at old homes. The outcome is the log of home price. Estimates have zero anticipation and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals and clustered at the parcel level are reported in parentheses.