Life After Lead : Effects of Early Interventions for Children Exposed to Lead

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Abstract

Lead pollution is consistently linked to cognitive and behavioral impairments, yet little is known about the benefits of public health interventions for children exposed to lead. This paper estimates the long-term impacts of early-life interventions (e.g. lead remediation, nutritional assessment, medical evaluation, developmental surveillance, and public assistance referrals) recommended for lead-poisoned children. Using linked administrative data from Charlotte, NC, we identify the impact of intervention based on inaccuracies in blood lead testing, which can alter intervention for individuals with similar lead exposure. We find that the negative outcomes previously associated with early-life exposure can largely be reversed by intervention.

Keywords: early childhood intervention, early health shocks, lead exposure, human capital formation

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Lead (Pb) pollution is a pervasive threat to childhood health and development since it is associated with substantial cognitive and behavioral impairments. Despite a dramatic decline in the prevalence of lead due to the prohibition of leaded gasoline, lead exposure is still widely recognized as a major public health issue. **?** estimate that approximately one out of every four homes in the United States contains a significant lead paint hazard. In 2000, the World Health Organization estimated that 40 percent of children under five have levels of exposure associated with neurological damage with 97 percent of these children living in developing countries (**?**). As is the case with other environmental hazards, lead is heavily concentrated in disadvantaged communities and therefore contributes to the intergenerational transmission of inequality through its impact on early-life health (**?**).

Given the large body of evidence connecting childhood lead exposure to cognitive and behavioral deficiencies,[2] the U.S. Center for Disease Control (CDC) recommends blood lead testing for children around one and two years of age and a case management approach for children whose detected blood lead levels (BLLs) exceed an alert threshold. To reduce childhood exposure and mitigate long-term damage, public health officials implement a combination of actions to both remove lead exposure through information and remediation as well as provide additional health and public assistance benefits for lead-poisoned children.

We merge blood lead surveillance data, public school records, and criminal arrest records at the individual level to evaluate the long-term impact of elevated BLL interventions on school performance and adolescent behavior in Charlotte,

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[2] **?** provides an extensive review of hundreds of studies investigating the effects of lead from epidemiology, toxicology, public health, nueroscience, and other medical disciplines. Early-life exposure is associated with the following: lower IQ , decreased test scores, increased rates of high school dropout, lower adult earnings, attention deficit disorders, impulsiveness, hyperactivity, conduct disorders, and criminal behavior (**?**).

North Carolina.[3] Similar to that of many other state and local health departments, the public health response in North Carolina is based on CDC guidelines. Two consecutive test results over an alert threshold of 10 micrograms of lead per deciliter of blood (μg/dL) triggers an elevated BLL intervention. Individuals exceeding this threshold only once do not require an intervention.

To identify a causal impact of elevated BLL interventions, we compare a range of behavioral and educational outcomes between our intervention group (two tests with BLL$\geqslant$10μg/dL) and control group (first test with BLL$\geqslant$10μg/dL and second test with 5μg/dL$\leqslant$BLL$<$10μg/dL). Variation in an individual's BLL results occurs due to inaccuracies in measuring exposure through blood tests and because lead has a short half-life (30 days) in the blood stream.[4] Conditional on a first test with a BLL exceeding the threshold, assignment to intervention will differ between individuals with similar lead exposure simply due to measurement error. We find support for this identification strategy by demonstrating balance on observable characteristics—including those highly correlated with exposure risk such as neighborhood and age of housing.

All cases with two BLL tests exceeding the initial alert threshold (10μg/dL) include the following actions: education for caregivers (which includes nutritional advice and information about reducing exposure in the home); a voluntary home environment investigation; and a referral to lead remediation services. A more intensive intervention can be triggered by tests over 15μg/dL or 20μg/dL. In addition to educating caregivers and providing a referral to remediation services, the intensive intervention typically includes: a mandatory home environment investigation; nutritional assessment; medical evaluation; developmental assessment; and a referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC).

We estimate a substantial decrease in antisocial behavior among individuals whose BLL test results trigger an intervention. Relative to our control group, we estimate a 0.167 standard deviation decrease in antisocial behavior using

[3] Charlotte contains the eighteenth largest school district and is representative of other large urban areas in the United States.

[4] Blood lead testing is the most common method to screen and diagnose lead exposure, but it is a fairly inaccurate measure of exposure due to high contamination risk during commonly used testing procedures (**???**). Moreover, blood lead tests do not measure cumulative exposure since the elimination half-lives for inorganic lead in blood is approximately 30 days (**?**).

a summary index. We also estimate a marginally significant 0.118 increase in educational performance among children eligible for an intervention several years before school entry.[5] These estimates are large in magnitude. In fact, the negative effects of high levels of exposure on antisocial behavior are nearly reversed by the intervention—children who test twice over the alert threshold exhibit similar outcomes as children with low levels of exposure (BLL$<5\mu$g/dL).

Our study offers two primary contributions. First, we provide novel estimates of the long-term impact of the standard public health response to elevated BLLs among young children in the United States. Since the CDC lowered the alert threshold to 10μg/dL and published new recommendations in 1991, millions of children in the United States have been eligible for the early-life health and environmental treatments following results of elevated blood lead levels.[6] Despite this large-scale public health response to lead-poisoned children, no previous studies have evaluated whether there are long-term behavioral or educational benefits associated with these environmental and health interventions.

Second, this paper contributes to a growing literature evaluating the causal impact of early-childhood health interventions on long-term cognitive and behavioral outcomes (**??**). Recent research suggests that early health and education interventions can yield large long-term benefits.[7] The Carolina Abecedarian Project—which provided a package of treatments focused on social, emotional, and cognitive development to disadvantaged children from birth through age five—has been associated with increases in educational attainment, reductions in criminal activity, and improved adult health (**???**). Many other early-life interventions have also proven effective, such as those administering increased medical care at birth (**?**); nutritional supplementation for pregnant women and young children (**?**); nurse home visit programs (**??**); and high-quality preschool programs such as Perry Preschool and Head Start (**????**). The elevated BLL

[5]For educational and behavioral outcomes we pool a large set of primary outcomes into two summary indexes to limit multiple hypothesis testing concerns previously identified among evaluations of early-life interventions (**?**).

[6]Since the CDC began collecting national statistics on blood lead surveillance in 1997, nearly one million children were confirmed to have elevated BLLs (BLL$>10\mu$g/dL) (surveillance statistics obtained from http://www.cdc.gov/nceh/lead/data/national.htm [accessed Jan 24 2015]). Projecting these testing rates and results back to 1991 implies millions of confirmed elevated BLL cases, which trigger intervention based on CDC recommendations.

[7]See **?** for a recent review.

intervention is unique to this literature because of its design and scale. The intervention collectively addresses several determinants of early-life health deficiencies and has been widely applied as a public health response to an environmental toxin.

The primary goal of intervention following a confirmed elevated blood lead level is to prevent further exposure and to reduce lead levels in affected children. Two primary channels emerge through which intervention affects antisocial behavior and cognitive outcomes. First, intervention may dramatically reduce the amount of continued childhood exposure to the dangerous neurotoxin by directly reducing exposure risks within the home environment. Benefits from reductions in environmental lead levels are expected given several recent studies showing strong quasi-experimental evidence of a causal relationship between exposure and long-term outcomes (**?????????**). While neurological damage from exposure prior to intervention may be irreversible, reductions in exposure following an intervention will limit the extent to which lead continues to impact early-childhood neurodevelopment.

Second, long-term benefits may occur through improvements in early-life health unrelated to any changes in lead exposure. The elevated BLL intervention package includes treatments previously demonstrated to impact later-life outcomes such as: visits from health workers; increased medical care; nutritional assessments and dietary modifications; and referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC).[8]

We cannot separately identify these two mechanisms or estimate the effects of specific elements of these elevated BLL intervention packages.[9] However, we do present evidence suggesting that both mechanisms contribute to long-term benefits. We find that households in our treatment group that are more

[8]Prior research documents long-term benefits from programs similar to each of these elements: increased medical care at birth (such as those triggered by Very Low Birth Weight evaluated by **?**); increased access to medical professionals (e.g. the Nurse-Family Partnership evaluated by **?**); improved early-life nutrition and increased access to public assistance programs (**??**); high-quality early childcare and preschool programs which focus on these social and cognitive developmental processes (e.g. Abecedarian, Perry Preschool, and Head Start).

[9]The majority of evaluations of other early-life interventions also estimate effects for an invervention package containing several components. For example, the original Abecedarian intervention combined early education with a nutritional and health component (**?**); **?** find long-term effects from a “bundle of medical interventions” triggered by a very low birth weight threshold.

likely to have reduced exposure, such as those with children who experience an immediate and sharp decline in post-intervention BLL test results, experience larger benefits. On the other hand, we estimate large effects for individuals eligible for treatments not directly addressing exposure risk, suggesting that long-term benefits should be at least partially attributed to general improvements in early-childhood health.

While further research is needed to investigate the mechanisms by which individuals benefit from elevated BLL interventions, cognitive and behavioral effects associated with the standard intervention package are still relevant in evaluating current public health policy. Public health organizations have recently stated that no BLL should be considered "safe" and have recommended lowering the threshold to identify additional children at risk for health and developmental problems caused by exposure to lead (**??**).[10] Applying similar interventions at lower BLL thresholds may yield a large return on investment considering the magnitude of our estimates and the large returns previously associated with other early childhood interventions.[11]

The remainder of the paper is structured as follows: Section 2 describes the early-life interventions triggered by elevated BLLs in Charlotte, NC. Section 3 describes our data and characterizes our intervention and control groups with summary statistics. Section 4 outlines our empirical strategy to identify causal effects of intervention. Section 5 presents and discusses estimated effects on a variety of educational and behavioral outcomes, and Section 6 investigates the mechanisms driving our main results. Finally, Section 7 provides some concluding remarks.

[10] The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch currently provides more information about nutrition and key sources of exposure for children testing over 5µg/dL.

[11] Cost benefit analyses of early-life intervention programs find a 4 to 1 return for Abecedarian (**?**) and a 7 to 1 return associated with Perry Preschool (**?**).

2. Description of Public Health Interventions Triggered by Elevated Blood Lead Levels

The U.S. Center for Disease Control and Prevention (CDC) currently funds the development of state and local childhood lead poisoning prevention programs and surveillance activities with the following objectives: to screen infants and children for elevated blood lead levels; to refer lead-poisoned infants and children to medical and environmental interventions; to educate healthcare providers about childhood lead poising; and to implement preventative measures to reduce childhood exposure (?). In 1991, the CDC defined a blood lead level of 10µg/dL as the "level of concern" and recommended the provision of specific medical and environmental services from public health agencies following blood lead tests exceeding this threshold (?).[12]

The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch bases intervention policies and procedures on CDC recommendations.[13] If a test indicates a blood lead level greater than 10µg/dL, a confirmation test is required within six months. If a second consecutive test indicates a blood lead level greater than 10µg/dL, a set of interventions is implemented based on the level of lead detected.[14] Figure A2 documents CDC recommendations as of 2002. Based on conversations with health workers in Mecklenburg County, NC, these CDC recommendations constituted public health policy in

[12] The intervention level was 25µg/dL between 1985 and 1991; 30µg/dL between 1975 and 1985; and 40µg/dL between 1970 and 1975 (?) .

[13] The state of North Carolina recommends blood lead tests for all children at age 12 months and again at age 24 months. In practice, the children screened for lead is limited to those individuals who live in neighborhoods with older homes (pre 1978) and when a child's parents answer "yes" or "don't know" to any questions on the CDC lead risk exposure questionnaire. The state of NC also requires lead testing for individuals participating in the Medicaid or WIC programs.

[14] The initial test is usually based on capillary specimens typically obtained by the a finger prick where the recommended procedure for a follow-up test is through venous blood draw, which is less likely to be contaminated. Surprisingly, the blood Lead Surveillance data indicate that approximately one-third of follow-up tests are venous during our sample period. The lack of compliance with this aspect of the CDC recommendations is potentially due to local health workers preferring the less-invasive capillary specimen method. We find no systematic differences across the treatment and control in the type of the confirmatory test and find that the initial lead value is not predictive of the second test type. These results indicate that the variation in confirmatory test type is likely due to resources available at the testing clinics and local health worker preferences.

Charlotte back to 1991.[15]

The set of interventions for our entire sample of children with two consecutive tests over 10μg/dL include the following: provision of nutritional and environmental information; a referral to WIC for families not already participating; an environmental history interview to identify sources of lead; and a referral to remediation programs for cases identified as high lead risk in the home. Tests over 15μg/dL or 20μg/dL can initiate a more intensive intervention in which children also receive the following treatments: a mandatory home environmental investigation; a medical evaluation; and a detailed nutritional assessment. We test for heterogeneous intervention effects for children with BLLs over these thresholds. According to conversations with individuals from the North Carolina Childhood Lead Poisoning Prevention Program, interventions are only substantially different at the 20μg/dL threshold in practice. This increase in intensity of intervention at the 20μg/dL threshold is evident in Figure A2 which emphasizes more direct medical and remediation action and is also supported by our estimates.

The formal protocol for the standard intervention includes first taking a medical history regarding any symptoms or developmental problems along with previous blood lead measurements and family history of lead poisoning. The healthcare provider then performs an environmental history interview during which family members are asked about the age, condition, and ongoing remodeling or repainting of a child's primary residence as well as other places where the child spends time (including secondary homes and childcare centers). The healthcare provider then determines whether a child is being exposed to lead-based paint hazards at any or all of these places. The environmental history also includes an inquiry about other sources of potential lead exposure.[16]

Based on the environmental history interview or a confirmatory test over

[15] We have found no evidence of any changes in policy preceding 2002 when the CDC recommendations were published in the NC Childhood Lead Poisoning Prevention Program lead testing manual. Since the mid 2000s, procedures have changed slightly to include the provision of nutritional and environmental information for individuals testing over 5μg/dL. However, during the time period when our sample was tested for lead (1990-2000), the 5μg/dL threshold did not trigger any policy interventions.

[16] Some additional sources of lead include Vinyl miniblinds manufactured prior to 1996, soil and dust which is primarily contaminated by previous existence of lead paint of leaded gasoline or pipes, as well as toys and pottery from overseas.

20µg/dL, a professional lead remediation team conducts a lead inspection at the child's home. This inspection leads to a determination of the home being lead-safe or in need of lead remediation. The provision of lead remediation services involves the removal of lead contaminants, which usually requires the replacement of windows and doors and the repainting of interior/exterior walls. During our sample time period, lead remediation was primarily funded through local government agencies, HUD based lead remediation grants, nonprofits and privately. The cost for lead remediation is not trivial with the average price of these repairs totaling $7,291.[17]

Since lead levels in the body are the result of a combination of lead exposure and the body's absorption of lead into the brain, nutrition can mitigate the effects of lead exposure. While the effectiveness of nutritional interventions is not established, research suggests that deficiencies in iron, calcium, protein, and zinc are related to BLLs and potentially increase vulnerability to negative effects of lead (?). A nutritional assessment includes taking a diet history with a focus on the intake of iron-, vitamin C–, calcium-, and zinc-rich foods. The nutritional information is also used to assess the ingestion of non-food items as well as water sources that contain lead for the family. The healthcare provider inquires into participation in WIC or the Supplemental Nutrition Assistance Program (SNAP or "food stamp") and refers the family to these programs if they are not currently participating. For children with a confirmatory test over 20µg/dL, a medical examination is conducted with particular attention to a child's psychosocial and language development. In cases of developmental delays, a standardized developmental screening test is recommended, which offers with referrals to an appropriate agency for further assessment.

3. Data

We merge blood lead surveillance data, public school records, and criminal arrest records at the individual level to evaluate the long-term impact of early-life intervention on school performance and adolescent behavior for individuals

[17] This estimated cost is based on cost data from LeadSafe Charlotte, which began operations in 1998 and was funded by HUD to remediate lead from homes in Charlotte.

born between 1990 and 1997 in Charlotte-Mecklenberg County, NC.[18] Blood lead surveillance data are maintained by the NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch.[19] This dataset includes BLL test results, which allow us to determine which children were eligible for various lead policy interventions due to two tests with BLLs of 10μg/dL or above.[20]

We match individual children who receive blood lead tests to two additional databases in order to examine the impact of elevated BLL interventions on educational and behavioral outcomes. First we match BLL test results to administrative records from Charlotte-Mecklenburg Schools (CMS) that span kindergarten through 12th grade and the school years 1998-1999 through 2010-2011.[21] Specifically, we incorporate student demographics on race and home address, yearly end-of-grade (EOG) test scores for grades 3 through 8 in math and reading, number of days absent, days suspended from school, and the number of incidents of school crime.[22]

To examine adult criminal outcomes, we match our lead database to a registry of all-adult (defined in North Carolina as age 16 and above) arrests in Mecklenburg County from 2006 to 2013.[23] The arrest data include information on the number and nature of charges as well as the date of arrest. These data allow us to observe adult criminality regardless of whether a child later transferred or dropped out of school, the main limitation is that it only includes crimes committed within Mecklenburg County.

[18] We restrict our sample to individuals born in 1997 or earlier to allow all individuals to reach age 16 by 2013.

[19] North Carolina requires all children participating in Medicaid or the Special Nutrition Program for Women, Infants, and Children (WIC) to be screened for lead at one or two years of age. Other children are screened if a parent responds "yes" or "don't know" to any of the questions on a CDC Lead Risk Assessment Questionnaire. Approximately 25 percent of the county's children were screened for lead in 2002.

[20] These data also include a child's name, gender, birth date, test date, BLL, and home address.

[21] We are able to match 74 percent of individuals with two tests and one test>10μg/dL in the blood lead surveillance data to a student record in CMS.

[22] According to NC State Statute 115C – 288(g), any incident at school involving any violent or threats of violent behavior, property damage, theft or drug possession must officially be reported to the NC school crimes division. This statute ensures that this measure of school crime is consistently reported across schools and cannot be treated differently based on school administrators.

[23] We use first name, last name and date of birth to link individuals across the two data sources. Details are provided in the Appendix.

We draw on two additional databases to control for parental and housing factors, which may influence outcomes. The first data are the population of birth certificate records from the state of North Carolina from 1990-1997 from which we obtain birth weight and years of parental education.[24] The second database is county assessor's data for all parcels. Property data can be matched to lead test results based on home address. We augment this parcel data with building permits for all home renovations between 1995 and 2012. This database allows us to incorporate information on housing stock and neighborhoods, directly accounting for some degree of home maintenance that may be correlated with lead exposure. This database on parcels allows us to generate variables for prior home renovations, age, and type of housing structure.[25]

Tables 1 and 2 display summary statistics for our intervention group and control group (defined in Section 4) after merging all data and limiting our analysis to individuals born prior to 1998. Tables A1 and A2 provide summary statistics for the entire population after merging all data. Not surprisingly, we observe lower educational and behavioral outcomes for children who receive a blood lead test compared to untested children and worse outcomes for those with high detected BLLs relative to those with miminal BLLs. Lead tests and higher test results are more likely among children living in older homes, lower income neighborhoods, and with less parental education. However, individual attributes are similar between the two groups in our estimation sample (Table 2), yet the intervention group has substantially better education and behavioral outcomes (Table 1).[26] Benefits from intervention are also evident from many of the panels of Figure 3, which displays mean outcomes for different first test BLLs as well as mean outcomes for the control group and intervention groups.

Given that our ability to match lead data varies across the administrative data sources, we are concerned that matches may be related to demographics or parental factors. Names from certain ethnic groups may have lower match rates

[24] We are able to match approximately 54 percent of birth records to our lead database. Even though this match rate is somewhat lower than our other databases, the variables from this database are simply used as control variables and we later show that this match rate is unrelated to our lead policy intervention group.

[25] The lead database is matched to parcel records 86 percent of the time with differences primarily a result of incomplete home address information.

[26] Summary statistics for summary index measures along with education and behavioral outcomes that are used to create the indices are presented in Table 1. A description of the indices is provided in Section 4 and the Appendix.

due to clerical errors and parents failing to properly fill out school forms or birth records may also be different in terms of parental supervision or guidance. Since we cannot directly test for the relationship between parental attributes and matches across databases, we provide a modified version of a balancing test in the bottom panel of Table A4 that determines if non-matched individuals are more likely to be assigned to the intervention group. In these results, we include all tested individuals in our intervention and control groups. Coefficients on indicators for matching a lead observation to the CMS schools records (school missing), parcel records (parcels missing), and birth records (mother's and father's education missing) are small and not statistically significant. We cannot reject the null hypothesis that lead tested individuals are no more likely to be successfully matched across databases for our intervention versus our control groups.

4. Empirical Framework

In order to assess the impact of the early-life interventions triggered by elevated BLLs, we estimate the following model:

$$Y_i = \alpha Intervention_i + \mathbf{X}_i \beta + \epsilon_i \tag{1}$$

where Y_i is an outcome for individual i and $\mathbf{X}_i$ includes a wide range of controls.[27] Each outcome is regressed on an indicator, $Intervention_i$, for whether child i received two consecutive tests over the intervention threshold of 10μg/dL. Since the presence of lead paint is heavily concentrated in older residential neighborhoods, standard errors are clustered at the Census Block Group (CBG) level.

Our primary results focus on intervention effects for two summary index outcomes: educational performance and adolescent antisocial behavior. We follow the methodology for creating a summary index as outlined in **?** in a re-

[27] We include indicators for gender, race/ethnicity, birth year, age at blood test, birth weight, parental education level, single family home, built pre 1978, controls for the average previous lead test results associated with the residential address listed, as well as Census Block Group 2000 variables for median household income, percent of families in poverty, and population density. A detailed description of these variables and their source is provided in the Appendix.

evaluation of several early childhood intervention programs.[28] Besides dealing with concerns about multiple hypothesis testing, a summary index can be potentially more powerful than individual-level tests due to random error in outcome measures. The antisocial behavior index includes measures of absences and number of days suspended (6th through 10th grade); school reported crimes, and adolescent criminal arrests from the age of 16 through 18. The educational performance index includes 3rd through 8th grade math and reading test score results as well as grade retention between 1st and 9th grade.[29] We also estimate and present results separately for individual outcomes used in the summary indexes.

Throughout the empirical analysis, we estimate Eq. (1) restricting our sample to individuals with an initial BLL test of 10µg/dL or greater. Our primary control group includes individuals who have one test over the alert threshold of 10µg/dL and the confirmatory test within six months between 5 and 9µg/dL. Despite the use of a threshold to determine intervention eligibility, we do not use a regression discontinuity design—comparing outcomes among those with a test just above versus just below the 10µg/dL threshold—because precise estimates from a regression discontinuity design are difficult given a small number of observations near the threshold. We report estimates from two variations of a regression discontinuity design in Appendix Table A10 and plot average index outcomes for the range of minimum BLL test results in Figure A1. Results using a regression discontinuity design are consistent with our later results, yet substantially less precise.

Our identification strategy relies on plausibly exogenous assignment of the intervention package within our estimation sample. In other words, conditional on an elevated BLL test result, drawing a second elevated BLL test value is unrelated to unobserved determinants of cognitive and behavioral outcomes. Several characteristics of blood lead testing support measurement error as a primary source of variation in test results. Blood testing is a noisy measure of

[28] The steps to calculate the summary index are outlined in detail in ?. We also provide a description of the steps in the Appendix.

[29] We limit our analysis to school outcomes through 10th grade because our public school records are available only through the 2010-2011 school year and we have very few cohorts in 11th or 12th grade by 2010. Criminal arrest data is available for an additional 2.5 years (through 2013) allowing us to measure arrests between 16 and 18 years of age for many of the children receiving lead tests since 1992.

exposure for two reasons: 1) a short half-life of lead in blood (30 days) and 2) a high risk of contamination during testing procedures that utilize capillary sampling (**???**). First, BLL levels are influenced by the relationship between date of exposure (which is usually unknown to the family) and the date of testing with only a month of passed time generating over a 50 percent decrease in the BLL. We expect similar decay even after an initial elevated BLL test due to the difficulty in scheduling and allocating time for a doctor's visit for this population of lower-income families. Second, capillary sampling (a "finger-prick" method) is the most common type of test for both initial and confirmatory tests in Charlotte during our time period of analysis and is known to have a high contamination risk relative to alternative testing procedures. Other non-blood testing procedures, such as measuring lead in children's teeth, are much more accurate but also much more expensive and therefore less prevalent.[30]

Consistent with these characteristics of testing, we observe a great deal of variation in test results in our sample. The first plot of Figure 1 (A) displays the distribution of BLLs for the first and second test; the second test shows higher BLLs on average, but there is still a similar amount of variation in test results across individuals compared with the first test. Part B of Figure 1 provides a visual investigation of the relationship between the first and second BLL test conditional on the age-at-test; the first and second test results appear to be randomly distributed along the 45 degree line indicating no systematic relationship between the first and second BLL test results that may occur from delays in obtaining a confirmatory BLL test for individuals with lower initial BLLs. Finally, Figure 2 illustrates the various combinations of the two BLL tests among all individuals with at least two tests; the vast majority of individuals receive a second test result different from their first.

Furthermore, Table 3 shows similar standard deviations in blood lead test results within parcel addresses (where underlying exposure levels should be similar) as compared to across parcel addresses.[31] This supports the notion that a significant component of testing variation is due to idiosyncratic measurement error; if

[30]Tooth lead testing is a more accurate measure of cumulative exposure since there is little risk for contamination and due to the fact that the elimination half-life for inorganic lead in bone is approximately 27 years (?).

[31]We removed individuals that received intervention to limit the effects of lead remediation on our measure of variation in BLL results.

blood lead testing was an accurate measure of true exposure, we would expect the variation within homes to be much smaller than variation across homes since the primary source of exposure is lead-based paint.

To assess whether intervention is unrelated to unobserved determinants of cognitive and behavioral outcomes, we compare observable characteristics (including measures of parental quality, health at birth, housing quality, and neighborhood quality) across the intervention and control groups. Despite large and statistically significant differences between mean outcomes in Table 1, we find no significant differences among observable characteristics between our intervention and control groups in Table 2.[32] The small differences in individual attributes between the intervention and control group is formally investigated in a balance test presented in Appendix Table A3 where an F-test shows that we cannot reject that all variables are jointly equal to zero.

To further show that intervention and control groups are similar, we use parcel addresses recorded in blood testing data for intervention and control groups and compare outcomes across those living in a "treatment" or control parcel *prior* to the child in our estimation sample. These treatment and control parcels were unlikely to be subject to any type of remediation and thus should offer similar levels of lead exposure.[33] Moreover, individuals in these homes should be similar in unobserved attributes since they sorted to the same residence as later treatment and control observations. Table 4 shows that individuals living in a home later occupied by a treatment child exhibit similar educational and behavioral outcomes as individuals in homes later occupied by a control child.

While a large fraction of the testing variation appears to be due to measurement error, two consecutive tests well over the threshold likely indicate a more dangerous level of underlying lead exposure which, based on previous literature, is associated with larger education and behavioral deficits. Thus, benefits associated with intervention would be biased downwards by negative effects of higher lead exposure among the intervention group. A downward bias implies that our results may represent conservative estimates of the long-term benefits associated with the interventions evaluated. To address this potential bias, Appendix

[32] We also conduct a formal balance test in Table A3 and find that observable characteristics are not predictive of intervention.

[33] We drop homes occupied by both treatment and control observations.

Table **??** show that our results are robust to models that control for BLL test type as well as limiting the control group to individuals with higher initial BLLs. Overall, our results do not indicate a substantial bias, suggesting that variation in test results does not necessarily reflect differences in underlying levels of exposure.

Throughout our analysis we refer to our estimates as intervention effects. However, our estimated effects represent a combination of several effects. First, since we do not directly observe participation in any intervention programs, our estimated effects are analogous "intention-to-treat" (or "ITT") treatment effects which represent a combination of the direct impact of intervention on outcomes and the probability of compliance with the intervention.[34] Second, the estimated impact includes the role of parental or other inputs that react to a confirmed elevated BLL. For example, intervention could directly impact child nutrition and the level of lead in the home environment but also impact the amount of care and attention provided by a parent. While decomposing the various components of this total effect would be extremely useful in designing early childhood intervention programs, our estimated intervention effect is the most relevant for evaluation of the CDC-recommended public health response to elevated BLLs. The effect of the policy will always include direct benefits of intervention, potential non-compliance, and any indirect benefits from family or community responses to intervention.

5. Results

After a second test confirms an elevated BLL, the NC Department of Health requires the implementation of the interventions recommended by the CDC (as listed in Figure A2). The CDC recommends testing until an individual with elevated levels tests below the alert threshold of 10μg/dL. To assess whether individuals comply with intervention after an elevated BLL is confirmed, we estimate the effect of intervention on several measures of continued testing. Columns (1) through (3) of Table 5 demonstrate that compared with the control

[34]It is possible that some families refuse any intervention after two consecutive tests over the alert threshold. These families would be "treated" in our framework since we do not observe implementation.

groups, those with confirmed elevated BLLs are 54 percentage points more likely to have a third test (74 percent of those with two tests over the threshold show up for a third test), have twice as many overall tests, and respond quickly following a second elevated test by obtaining a third test within approximately three months. Overall, 79 percent of individuals in our intervention group continue testing until their BLL$\leqslant$10μg/dL. While these results provide some confidence that, on average, interventions are administered to children who are supposed to receive them according to local health department policy, all of our estimates remain "intention-to-treat" estimates since we do not have data indicating participation in the components of the intervention package.

A large literature across multiple disciplines consistently associates lead exposure with lower cognitive outcomes, including measures of educational performance (**?**).[35] Improvements in educational outcomes are also consistently linked to early-life health and education interventions (**?**). The first panel of Table 6 estimates Eq. (1) for our education summary indexes and for individual outcomes grouped by different grade levels. Combining math and reading test scores between the 3rd and 8th grade as well as grade retention outcomes between the 1st and 9th grade into a summary index, we estimate a marginally significant 0.118 standard deviation increase in educational performance associated with the elevated BLL intervention. While the majority of our test score estimates are imprecise, they are at least consistent with benefits from intervention in direction and magnitude.

Early-life lead exposure is linked to increases in behavioral problems, conduct disorders, and adult criminal activity (**?**).[36] Moreover, early-life childcare and nurse-family partnership interventions have been shown to reduce delinquent and criminal behavior among treated individuals (**?**). The second panel of Table 6 reports a large and significant decline in antisocial behavior associated with elevated BLL intervention. Relative to the control group, we estimate a 0.167 standard deviation decrease in our antisocial behavior summary index associated

[35] Effects are found across different measures of cognition and academic performance such as: IQ tests (**?????**), primary school assessments (**????????**), high school graduation (**???**), and even lower adult earnings (**?**). **?** reviews many other studies.

[36] Lead has been found to impact externalizing behaviors such as attention, impulsivity, and hyperactivity in young children (**??**). These behavioral effects translate to increased delinquent and antisocial activity (**???**) as well as higher rates of arrest (**????**). **?** reviews many other studies.

with intervention. This represents a very large drop from the average index value of 0.10 for the control group. The pattern of estimates across individual outcomes of suspensions, absences, school crimes, and criminal arrests reported in Table 6 consistently demonstrates improvements associated with intervention.

We conduct several robustness checks in Appendix Table **??**. First, we show that our results do not depend on the specification of our primary control group (one test with BLL⩾10μg/dL and a second test with 5⩽BLL<10μg/dL). We obtain similar estimates to those presented in Table 6 for the following control groups: one test exceeding 10 and any second test under 10μg/dL; only individuals with one test over 10μg/dL who do not return for a follow-up test; all individuals with at least one test result yielding a BLL⩾5μg/dL; and only individuals with an initial test with BLL⩾15μg/dL. Finally, we estimate similar effects including indicator variables for each initial BLL test result (initial BLL fixed effects). Estimates including initial BLL fixed effects are about 30 to 40 percent smaller in magnitude and not statistically significant, which is not surprising given we have much less variation in intervention status within fixed initial BLL test results. These final two robustness checks (initial BLL>15μg/dL and initial BLL fixed effects) suggest there is a limited concern of downward bias in our estimated intervention effects from higher levels of lead exposure. Results from models including indicator variables for initial BLL test results also allow us to test whether behavior following an initial elevated BLL test could lead to systematic differences in the composition of our intervention and control groups since both groups receive the same initial information shock.

As a falsification test, we estimate whether individuals with two consecutive tests above other arbitrary thresholds (Bll=3μg/dL, BLL=5μg/dL, and BLL=7μg/dL) experience any benefits relative to those with one test over the false threshold and one test just under. Results are presented in Table A8. We find no evidence that individuals with two consecutive tests over a false threshold benefit along our index outcome measures. These results help dispel any concerns about a correlation between unobserved family attributes and the likelihood of two consecutive tests within a similar range or above a certain threshold.

We estimated heterogeneous effects across different demographic groups but estimates are noisy due to a small number of “treated” individuals in each subsample.[37] Overall, estimates suggest slightly larger benefits for female children and those with parents who did not graduate from high school. Larger treatment effects for females are also found across evaluations of other early childhood interventions (see **?** for a summary of results across multiple studies).

Finally, we match intervention and control individuals to siblings in our data to test whether elevated BLL intervention impacts other children in the household. Table A9 displays estimates from Eq. (1) for the small number of siblings we were able to match to our sample of intervention and control children. Estimated intervention effects for siblings of intervention and control individuals are consistent with there being an effect of intervention for the household, but these benefits are concentrated among younger siblings. To the extent interventions reduce levels of dangerous lead exposure, we expect larger effects for younger siblings since older siblings would already be damaged from exposure. However, we interpret these results cautiously since they are based on few observations and are associated with large standard errors.

6. Mechanisms and Intensity of Treatment

The substantial improvements associated with the elevated BLL interventions likely represent a combination of direct and indirect effects from both the local health department's response and the parental response to lead exposure. Two primary channels emerge through which intervention affects antisocial behavior and cognitive outcomes. First, intervention may dramatically reduce the amount of continued exposure to the dangerous neurotoxin by directly reducing exposure risks within the home environment. Second, long-term benefits may occur through improvements in early-life health unrelated to any changes in lead exposure.

As previously discussed in Section 2 and evident in Figure A2, higher intensity interventions are recommended following confirmatory tests over 15μg/dL and 20μg/dL. We explore whether these higher-intensity interventions are associated with larger benefits in the first panel of Table 7. We find substantial

[37] For example, the number in the intervention group whom have birth records indicating a parent without a high school degree is 25.

benefits among those with a confirmatory test over 20μg/dL and do not detect any additional benefits for those with a confirmatory test between 15 and 20μg/dL. Additional effects at the 15μg/dL threshold are not expected in this setting since, according to individuals at the North Carolina Childhood Lead Poisoning Prevention Program, interventions are only substantially different at the 20μg/dL threshold in practice. These results suggest larger benefits from more intensive interventions but are based on a small number of individuals. The larger effects also do not help distinguish between mechanisms since the higher-intensity intervention is associated with more targeted efforts to reduce exposure through mandatory home investigations but is also associated with an increase in medical attention, developmental surveillance, and access to public assistance programs. These results do suggest that the intensity of the local health department's response is potentially an important determinant of long-term benefits and are consistent with prior evaluations of early-life programs. Our point estimates of the lower intensity intervention suggest some benefit, but are not statistically significant which is not surprising given the general lack of power to detect statistically significant effects on subsamples of our treatment group.[38]

Following a second elevated BLL test result, nearly 80 percent of individuals continue to get tested until their BLLs drop below the alert threshold of 10μg/dL. While many will eventually test below the threshold due to the idiosyncratic variation in testing procedures previously discussed, many likely have lower BLLs due to some effort to reduce the risk of exposure in the residential environment. Reduction in exposure could be due to a parental response to information provided through discussions with health workers following a confirmatory elevated BLL test result or through instructions provided following a home-environment inspection. Reduction could also be due to the provision of remediation services following a home investigation or a referral to available remediation programs.

The most immediate (and expensive) way to reduce environmental exposure

[38]While an important aspect of the lower intensity interventions is parental education about ways to control household exposure, they also provide nutritional information and a referral to remediation services. Thus, these estimated (imprecise) benefits are not inconsistent with previous randomized control trials that do not find large or significant BLL reductions when evaluating parental education and "household dust control" interventions (**?????**).

within residences identified to contain a lead hazard is through a remediation service. Prior evaluations of household lead remediation programs through randomized controlled trials document significant decreases in levels of household dust (?) and the number of elevated BLL cases (?). If an inquiry or home investigation identifies a potential residence-based hazard for children exceeding the alert threshold, families are typically referred to lead-based paint removal programs. Since 1998, LeadSafe Charlotte, a HUD-funded organization, has provided remediation services to eligible families. While we obtained application and remediation data from this program and are able to match to Charlotte properties, our estimation sample spans birth cohorts between 1990 and 1997, so we cannot match most individuals to remediation services closely following elevated test results. However, we do find a positive association between intervention and whether the parcel was eventually remediated through the LeadSafe Charlotte program in column 4 of Table 5. The magnitude of this coefficient indicates that intervention households were more than three times as likely to have lead remediation as our control group.

To further investigate whether benefits may be due to reductions in levels of exposure, Table 7 compares estimated intervention benefits across individuals in the intervention group who are more likely to have directly addressed lead exposure problems. First, we find larger effects for individuals experiencing a significant drop (more than 5μg/dL) between the second and third BLL test. Individuals who experience a sharp drop in BLLs after two consecutive tests over the alert threshold are more likely to have benefited from a reduction in exposure. We also estimate separate intervention effects for individuals who respond quickly by re-testing within one month following a second test over the alert threshold. The direction of both of these estimates suggests benefits from directly addressing exposure risk.

We also compare outcomes across those living in a "treatment" or control parcel *after* the child in our estimation sample. Table 8 presents results from a specification where individuals living in an intervention parcel after the time of intervention are generally better off along education and behavioral outcomes compared to those living in control households. Also, as discussed earlier, we did not detect any difference in outcomes for individuals matched to the intervention and control parcels *prior* to BLL testing of our estimation sample. Again, these results mildly suggest that parcels containing a child in the intervention group experience long-term lead exposure reductions.

7. Conclusion

In this first evaluation of the standard public health response to high levels of exposure to environmental lead, we find evidence that interventions can affect long-term educational and behavioral outcomes. We estimate far-reaching decreases in antisocial behaviors (suspensions, school crimes, unexcused absences, and criminal activity) and, to a lesser extent, increases in educational performance. These results support recent evidence that early-life interventions can mitigate and compensate for the deleterious effects of lead.

A massive amount of evidence across multiple disciplines consistently points to a lasting negative impact of lead exposure. In fact, recent studies and media reports suggest that reductions in lead exposure through the prohibition of leaded gasoline may be one of the most important determinants of the decline in crime rates over the past two decades in the United States and other developed nations.[39] However, not much is known to what types of programs and policies are effective in addressing these effects. While randomized controlled trials have been used to evaluate other large-scale early childhood interventions (e.g. Head Start), this paper demonstrates that evaluations of interventions related to lead exposure can be conducted using administrative data and by exploiting institutional features (such as testing procedures) to construct a valid counter-factual or control group to evaluate causal effects of intervention.

Although exposure to lead has been reduced in most countries due to the prohibition of leaded gasoline, lead exposure still represents a major public health issue. In the United States, children have continued to be exposed to lead over the last several decades as a result of deteriorating lead paint and contaminated dust within older housing units (**???**). The National Survey of Lead and Allergens in Housing estimated that 38 million housing units in the United States (40 percent of all housing units) contained lead-based paint, and approximately 24 million had significant lead-based paint hazards (**?**). Recognizing the current

[39]Recent media articles **?** and **?** highlight this connection based on results from papers by **????**.

threat to child health and development in California, a Superior Court judge recently ordered three paint companies to contribute $1.15 billion to fund the inspection, risk assessment, and hazard abatement of older homes in ten California jurisdictions (**?**).[40]

Lead exposure is a more pressing public health issue in developing countries where lead in petrol, industrial emissions, paints, ceramics, food and drink cans, water pipes, and traditional medicines is more prevalent. In an evaluation for the World Health Organization, **?** estimates that 120 million people have blood lead concentrations above 10μg/dL, accounting for an estimated 0.9 percent of the global burden of disease. **?** also estimates that nearly 10 percent of children under five in the world have blood lead levels greater than 20μg/dL with 99 percent of these children living in developing countries. There is a great deal of evidence that these levels of exposure cause drastic cognitive and behavioral impairment and policies to reduce exposure in developing countries should be of first-order importance.

Until countries and communities make long-run investments in reducing environmental exposure, our results suggest that intervening early is critical to limit the damage from exposure. Our research can be used to inform policymakers considering intervention at lower levels of detected exposure. In 2012, the CDC recognized a lack of evidence for any BLL to be considered "safe" and recommended using a lower threshold to identify children at increased risk for health and developmental problems caused by exposure to lead (**?**).[41] It is likely that increasing the frequency and intensity of intervention for lead-exposed children will yield a profound return considering the potential long-term effects of lead on health and human capital.

[40] Judgement was issued for the Plaintiff, the People of the State of California, against Defendants ConAgra Grocery Products Company, NL Industries, Inc. and The Sherwin-Williams Company.

[41] The NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch currently provides more information about nutrition and key sources of exposure for children testing over 5μg/dL. The European Food Safety Authority and the World Health Organization have also recently concluded that there is no known safe level of exposure **?**.

Table 1: Means of education and behavior outcomes for intervention and control groups

	Intervention	Control	Difference
Blood lead level (µg/dL)	17.85	12.09	5.76***
	(8.25)	(4.41)	(0.73)
Education Index	0.08	−0.05	0.13*
	(0.60)	(0.71)	(0.08)
Reading Test Score (avg 3-5th grade)	−0.44	−0.58	0.14
	(0.83)	(0.91)	(0.12)
Math Test Score (avg 3-5th grade)	−0.46	−0.53	0.07
	(0.81)	(0.96)	(0.12)
Repeat a grade (grades 1-5)	0.15	0.14	0.01
	(0.36)	(0.35)	(0.04)
Reading Test Score (avg 6-8th grade)	−0.32	−0.50	0.18
	(0.81)	(0.95)	(0.12)
Math Test Score (avg 6-8th grade)	−0.31	−0.43	0.12
	(0.82)	(0.88)	(0.11)
Repeat a grade (grades 6-9)	0.14	0.21	−0.07
	(0.35)	(0.41)	(0.05)
Adolescent Antisocial Behavior Index	−0.15	0.10	−0.25***
	(0.47)	(0.83)	(0.08)
Total Days Suspended from School (6th-10th grade)	9.25	17.67	−8.42***
	(15.80)	(32.44)	(3.20)
Total Days Absent (6th-10th grade)	30.61	45.65	−15.05***
	(36.31)	(54.71)	(5.70)
Total School Reported Crimes/Incidents (6th-10th grade)	1.97	3.45	−1.47**
	(3.40)	(6.75)	(0.67)
Ever Arrested	0.08	0.18	−0.10**
	(0.27)	(0.38)	(0.04)
Ever Arrested - Violent	0.03	0.12	−0.09***
	(0.16)	(0.32)	(0.03)
Ever Arrested - Property	0.04	0.07	−0.03
	(0.20)	(0.26)	(0.03)
Observations	119	182	301

Means and standard deviations are reported above for Intervention and Control Groups. Standard errors are reported for the difference with * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Individuals are categorized by their first BLL test result for summary statistics by blood lead level results.

We follow the methodology for creating a summary index as outlined in **?** in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results and grade retention between 3rd and 9th grade. The antisocial behavior index includes measures of number of days suspended and absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

End-of-Grade Test scores for grades 3 through 8 are given mean zero and standard deviation of one based on NC state average test score.

All models restrict our sample to individuals born in 1997 or earlier in order to allow all individuals to reach age 16 by 2013.

Control includes only individuals who received one test $\geqslant 10\mu g/dL$ and a second test $\geqslant 5\mu g/dL$ but $< 10\mu g/dL$.

Table 2: Means of demographic, housing, and neighborhood characteristics for intervention and control groups

	Intervention	Control	Difference
Background Characteristics			
Male	0.61	0.58	0.02
	(0.49)	(0.49)	(0.06)
Minority	0.77	0.77	0.00
	(0.42)	(0.42)	(0.05)
Stand Alone Residence	0.58	0.57	0.00
	(0.50)	(0.50)	(0.06)
Home Built pre 1978	0.79	0.78	0.01
	(0.41)	(0.42)	(0.06)
Past Lead Tests at a Home (mean μg/dL)	4.40	4.52	−0.12
	(1.16)	(1.51)	(0.25)
Age at Blood Lead Test	1.81	1.73	0.08
	(1.34)	(1.13)	(0.14)
Father Education (years)	12.31	12.59	−0.28
	(2.63)	(2.32)	(0.46)
Mother Education (years)	11.92	11.45	0.47
	(2.96)	(2.28)	(0.37)
Birth Weight (ozs)	115.09	110.90	4.20
	(20.37)	(21.57)	(3.04)
CBG Population Density (000s/sq mile)	3.30	3.31	−0.01
	(2.06)	(2.22)	(0.25)
CBG Median HH Income	38.78	36.60	2.18
	(22.25)	(17.65)	(2.31)
CBG Percent in Poverty	0.48	0.56	0.08
	(0.41)	(0.46)	(0.05)
F-stat (p-value)			0.410
Observations	119	182	301

Means and standard deviations are reported above for Intervention and Control Groups. Standard errors are reported for the difference with * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Individuals are categorized by their first BLL test result for summary statistics by blood lead level results.

The reported p-value in the third column is the result of an F-test of joint-significance of all of the reported variables in a regression with an intervention indicator as the dependent variable. The full balance test is reported in Appendix Table A3.

All information regarding housing or Census Block Group (CBG) 2000 neighborhood is based on address given at the time of the first lead test.

Control includes only individuals who received one test $\geqslant$10μg/dL and a second test $\geqslant$5μg/dL but $<$10μg/dL.

Table 3: Testing Variation

	1st BLL Test *Standard Deviations*	2nd BLL Test *Standard Deviations*
Unconditional		
Across Homes	2.73	1.98
Within Homes	1.98	1.52
Conditional on child attributes		
Across Homes	2.52	1.87
Within Homes	1.92	1.46
Observations	19,731	9,457

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

Each cell contains the standard deviation of BLL test values that correspond to row and column headings. In the case of multifamily structures, within home variation includes across apartment variation of BLLs. We drop all observations (N=992) for lead tested individuals in a parcel with a treatment observation in computing Within Home Standard Deviations in order to limit to effects of lead remediation on our results. Lead remediation programs were greatly expanded only after our sample of lead tests. Conditional on student attributes standard deviations based on running a first stage model of BLL on covariates for gender, race, birth year, age at testing, housing attributes, parental education, birth weight and Census Block Group 2000 variables and using the estimated residual to calculate standard deviation across and within homes.

Table 4: Educational and Behaviorial Outcomes - Prior Residents

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Intervention Parcel	0.030	0.001
	(0.049)	(0.047)
Observations	1,363	1,363

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

We follow the methodology for creating a summary index as outlined in **?** in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results and grade retention between 3rd and 9th grade. The antisocial behavior index includes measures of number of days suspended and absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

The sample used in this table is based on individuals that lived at the same address *prior* to our sample of treatment and control observations. We also drop any parcels that contain both treatment and control observations.

Table 5: Do Individuals Comply with the Intervention?

	(1) Had 3rd BLL Test	(2) Total # of BLL Tests	(3) Months b/t 2nd & 3rd Test	(4) Future Lead Remed-iation
Intervention	0.527***	2.596***	−7.389***	0.073**
	(0.042)	(0.279)	(1.317)	(0.034)
Dep. Var. (mean) for Control Group	0.22	2.33	11.62	0.03
Observations	368	368	136	368

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

The sample is larger for this table since we no longer need to restrict our data to individuals that can be matched with school records. The fewer observations for column three are simply due to the limited number of individuals that had third tests.

Table 6: Effects of an elevated BLL intervention on education and behaviorial outcomes

	(1) Education Index	(2) Reading (3-5th)	(3) Math (3-5th)	(4) Repeat Grade (1-5th)	(5) Reading (6-8th)	(6) Math (6-8th)	(7) Repeat Grade (6-9th)
Intervention	0.112*	0.162	0.109	0.043	0.177*	0.132	−0.044
	(0.067)	(0.123)	(0.116)	(0.041)	(0.100)	(0.098)	(0.044)
Observations	301	240	244	301	235	236	301

	(1) Adolescent Antisocial Behavior Index	(2) Days Suspended (6-10th)	(3) Days Absent (6-10th)	(4) School Crimes (6-10th)	(5) Ever Arrested	(6) Ever Arrested Violent	(7) Ever Arrested Property
Intervention	−0.161**	−5.142**	−7.655*	−1.080*	−0.067	−0.063**	−0.010
	(0.077)	(2.465)	(4.015)	(0.589)	(0.043)	(0.029)	(0.037)
Observations	301	301	301	301	301	301	301

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

We follow the methodology for creating a summary index as outlined in **?** in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results and grade retention between 3rd and 9th grade. The antisocial behavior index includes measures of number of days suspended and absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

End-of-Grade Test scores for grades 3 through 8 are given mean zero and standard deviation of one based on NC state average test score.

All models restrict our sample to individuals born in 1997 or earlier in order to allow all individuals to reach age 16 by 2013.

Control includes only individuals who received one test $\geqslant 10\mu g/dL$ and a second test $\geqslant 5\mu g/dL$ but $< 10\mu g/dL$.

Table 7: Heterogeneous Effects by Intensity of Intervention

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Intervention (20+)	0.211	−0.215*
	(0.162)	(0.116)
Intervention (15+)	0.002	0.017
	(0.121)	(0.113)
Intervention (10+)	0.041	−0.126
	(0.074)	(0.092)
Observations	301	301
Intervention*Large Drop in BLL	0.095	−0.212**
	(0.142)	(0.101)
Intervention	0.088	−0.108
	(0.069)	(0.084)
Observations	301	301
Intervention*Quick Time to Next BLL Test	0.121	−0.051
	(0.151)	(0.103)
Intervention	0.099	−0.155**
	(0.070)	(0.076)
Observations	301	301

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

We follow the methodology for creating a summary index as outlined in **?** in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results and grade retention between 3rd and 9th grade. The antisocial behavior index includes measures of number of days suspended and absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

In the top panel of this table, we include indicators for potentially higher intensity treatment categories based on thresholds outlined in CDC recommendations summarized in Figure A2. We create indicators for those within the treatment group who have a test above 15µg/dL and those with a test above 20µg/dL. Note that these indicators are not mutually exclusive; An individual with a confirmatory test over 20 would have each of the three treatment level indicators equal to one. Individuals exceeding the 20µg/dL threshold receive an intervention involving more intensive case management, medical evaluations, and nutritional interventions. Some local health agencies apply these higher level interventions at the 15µg/dL, but based on conversations with the North Carolina Blood Lead Surveillance Group, the 20µg/dL threshold is almost always used to distinguish the higher-intensity treatment in practice. Children testing between 10-19µg/dL receive an intervention primarily focused on the provision of information about lead exposure reduction and nutrition. For the second panel and third panel of the table, we test for heterogenous effects for other measures potentially capturing the intensity of the response to confirmed elevated blood lead levels. In the second panel, we define large drop as those individuals that see a drop in BLL of more than 5 BLL between 2nd and 3rd test. In the third panel, we define quick time between 2nd and 3rd test based on less than 1 month between 2nd (confirmatory) test and a 3rd BLL test.

Table 8: Education and Behaviorial Outcomes - future residents

	(1) Education Index	(2) Reading (3-5th)	(3) Math (3-5th)	(4) Repeat Grade (1-5th)	(5) Reading (6-8th)	(6) Math (6-8th)	(7) Repeat Grade (6-9th)
Intervention Parcel	0.100	0.080	0.033	−0.024	0.112	0.043	−0.033
	(0.076)	(0.099)	(0.097)	(0.034)	(0.115)	(0.112)	(0.042)
Observations	430	348	351	430	335	335	430

	(1) Adolescent Antisocial Behavior Index	(2) Days Suspended (6-10th)	(3) Days Absent (6-10th)	(4) School Crimes (6-10th)	(5) Ever Arrested	(6) Ever Arrested Violent	(7) Ever Arrested Property
Intervention Parcel	−0.133	−2.000	−2.641	−0.396	−0.069***	−0.031**	−0.053***
	(0.093)	(2.390)	(5.063)	(0.685)	(0.025)	(0.014)	(0.020)
Observations	430	430	430	430	430	430	430

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

We follow the methodology for creating a summary index as outlined in **?** in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results and grade retention between 3rd and 9th grade. The antisocial behavior index includes measures of number of days suspended and absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18.

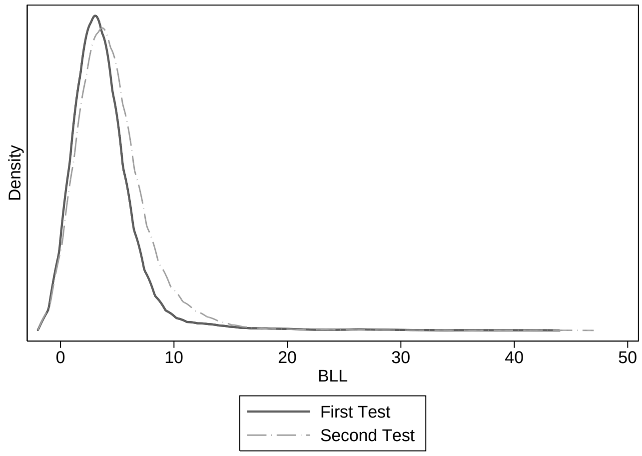
End-of-Grade Test scores for grades 3 through 8 are given mean zero and standard deviation of one based on NC state average test score.

All models restrict our sample to individuals born in 1997 or earlier in order to allow all individuals to reach age 16 by 2013.

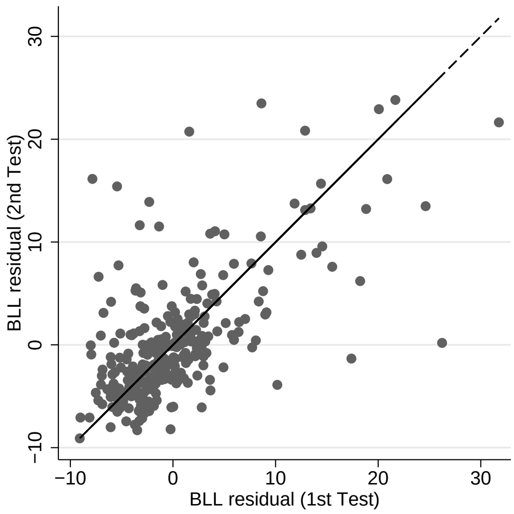
The sample used in this table is based on individuals that lived at the same address *after* our sample of treatment and control observations. We also drop any parcels that contain both treatment and control observations.

Figure 1: Blood Lead Testing Variation

A: Distribution of BLL test results

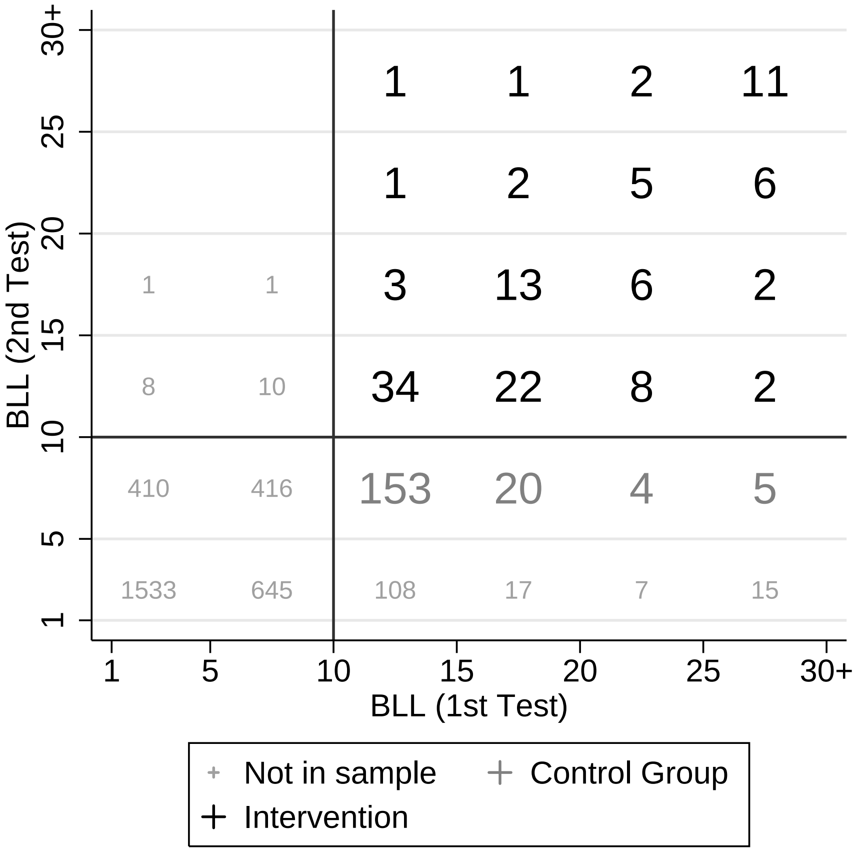


B: Test residuals conditional on age



Panel A of the figure provides the distribution of first and second BLL tests for the full blood surveillance dataset. Panel B plots residuals from regressions of blood lead test results on flexible age-at-test polynomials. The relationship between the first and second test results (not explained by the age of the tested individual) appears to be randomly distributed along the 45 degree line indicating no systematic relationship between the first and second test result.

Figure 2: Observations by First and Second BLL Test



This figure provides a grid with 1st and 2nd BLL test result values indicating treatment and control regions and highlights the variation in BLL between the first and second BLL test as well as the number of observations in our estimation sample for various combinations of first and second BLL test results.

Figure 3: Average Outcomes by Blood Lead Level

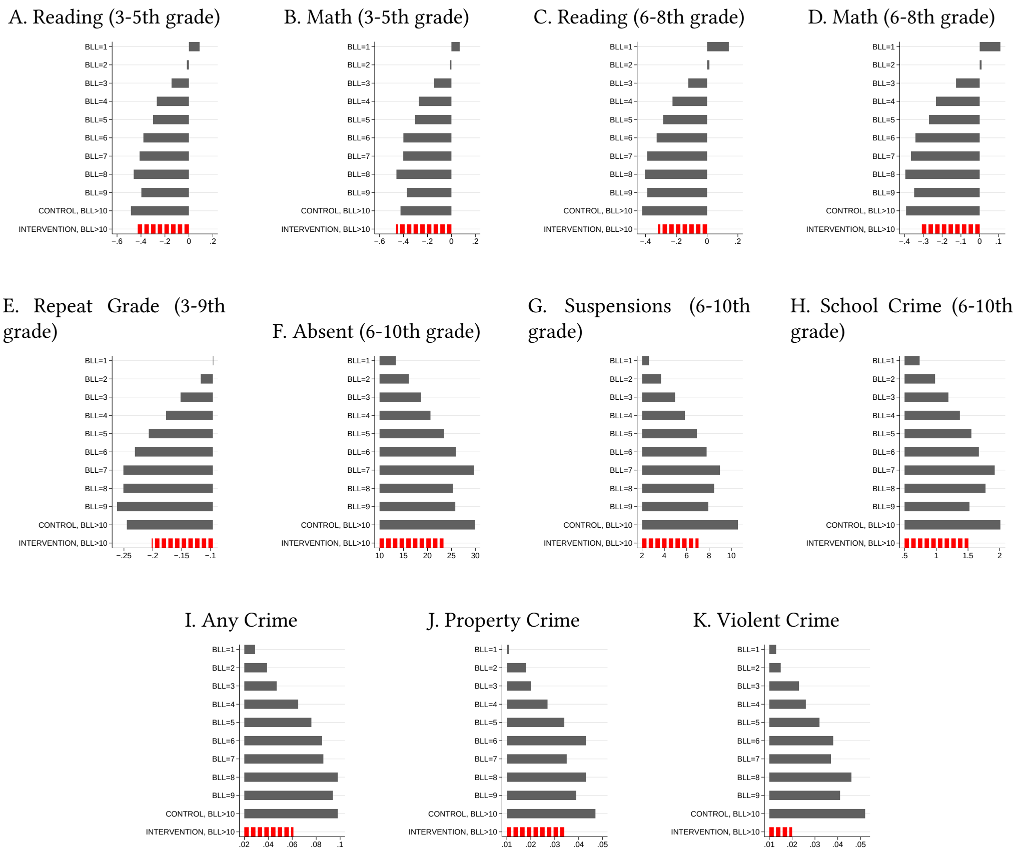


Figure Note: This figure depicts mean outcomes by the level of initial BLL test result. End-of-Grade Test scores based on 3rd through 8th grades and given mean zero and standard deviation of one based on NC state average test scores. Average Test Scores incorporate all test scores from grades 3rd-5th or 6th-8th and years for which a student is missing is not computed in the average. Days absent, suspended and reported crimes at school are based on totals for those students from 6th through 10th grades. Arrest Outcomes measure the proportion of individuals in each group who are arrested for any crime, property or violent crime.

Appendix (*For Online Publication*)

A. Background on Data Sources and Sample Construction

Our primary source of data is the blood lead surveillance data from the state registry maintained by the NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch. This dataset includes a child's name, gender, birth date, test date, blood lead level (BLL) and home address. The North Carolina State Laboratory for Public Health (Raleigh, NC) conducted 90 percent of the lead analyses of the blood samples and all BLL values are stored as integers with a value of 1μg/dL (micrograms per deciliter) given to children without any detectable lead.

Our analysis focuses only on children living in Mecklenburg County and includes all BLL tests for a child between 1993 and 2008. North Carolina requires all children participating in Medicaid or the Special Nutrition Program for Women, Infants and Children (WIC) to be screened for lead at 1 or 2 years of age. Other children are screened if a parent responds "yes" or "don't know" to any of the questions on a CDC Lead Risk Assessment Questionnaire. Approximately 25 percent of the county's children were screened for lead in 2002. This dataset provides multiple blood lead level tests per child which allows us to determine which children received various lead policy interventions due to two tests with BLL of 10μg/dL or above.

We subsequently match individual children to two additional databases in order to examine the impact interventions on educational and behavioral outcomes. All matches are conducted using first and last name as well as date of birth and will incorporate fuzzy matches for names in some cases. Our first database is the administrative records from Charlotte-Mecklenburg Schools (CMS) that span kindergarten through 12th grade and the school years 1998-1999 through 2010-2011. This dataset includes each student that attended a public school in the City of Charlotte for at least one semester and provides annual data for each year of matriculation. Specifically, we incorporate student demographics on race and home address, yearly end-of-grade (EOG) test scores for grades 3 through 8 in math and reading, number of days absent, days suspended from school as well as the number of incidents of school crime.[42] We are able to match 65 percent of lead tests to a student record in CMS. This match rate improves to 74 percent for our policy sample of individuals with two tests and one test>10µg/dL.

In order to examine adult criminal outcomes we match our lead database to a registry of all adult (defined in North Carolina as age 16 and above) arrests in Mecklenburg County from 2006 to 2013. We use first name, last name and date of birth to link individuals across the two data sources. While over 90 percent of the matches are exact, we recover additional matches using an algorithm for partial matches that has been used and validated in **?**. The Mecklenburg County Sheriff (MCS) tracks arrests and incarcerations across individuals using a unique identifier that is established with fingerprinting. The arrest data include information on the number and nature of charges as well as the date of arrest. This data allows us to observe adult criminality regardless of whether a child later transferred or dropped out of CMS schools with the main limitation being that it only includes crimes committed within Mecklenburg County. The quality of matching between the lead and arrests databases is not directly measurable since one cannot distinguish between those lead tested individuals never arrested versus individuals who do not match due to clerical errors in names or moving out of the county. We can speak to the quality of matches using the arrest database by the fact that we are able to match approximately 94 percent of arrest records for a given cohort to our CMS education database.

In order to provide some basic controls for parental and housing factors, we draw on two additional databases. The first database is the universe of birth certificate records from the state of North Carolina from 1990-2002. As with previous databases, we are able to match our lead database to the birth records database using name and date of birth. In the case of birth records we are primarily interested in two variables, father's and mother's years of education. We are able to match approximately 54 percent of birth records to our lead database. Even though this match rate is somewhat lower than our other databases, the variables from this database are simply used as control variables and we later

[42] According to NC State Statute 115C – 288(g), any incident at school involving any violent or threats of violent behavior, property damage, theft or drug possession must officially be reported to the NC school crimes division. This statute ensures that this measure of school crime is consistently reported across schools and cannot be treated differently based on school administrators.

show that this match rate is unrelated to our analysis of lead policy interventions. The second database is county assessor's data for all parcels on an annual basis from 2002-2012 in Mecklenburg County, NC. For this database, we match our lead data to parcel records based on home address given for an individual's first lead test. We augment this parcel data with building permits for all home renovations from 1995-2012. This database on parcels allows us to generate variables for prior home renovations, age and type of housing structure. We also create a measure of unobserved housing quality through the use of the residual from a simple housing price hedonic of property and neighborhood attributes on assessed value in 2002. The lead database is matched to parcels records 86 percent of the time with differences primarily a result of incomplete homes address information.

In some of our analysis, we merge into our dataset two additional data elements. First, we merge data from the LeadSafe Charlotte program which contains detailed data on the addresses of approximately 2,500 homes (single-family and multi-family) which have been lead inspected or lead remediated and certified lead safe since 1998. We match LeadSafe addresses to our county parcel data based on parcel addresses with 20 LeadSafe homes unable to be successfully matched to parcel records. Second, we construct a measure of siblings using birth records data. In order to be characterized as a sibling, two individuals must share a mother's first name, last name and date of birth based on Mecklenburg County birth records.

B. Summary Index Construction

We follow the methodology in **?** to create two summary index outcome measures: educational performance and adolescent antisocial behavior. The antisocial behavior index is created to include measures of number of days suspended and unapproved absences (6th through 10th grade), school reported crimes, and criminal arrests between the ages of 16 and 18. The education index includes 3rd through 8th grade math and reading test score results and grade retention between 1st and 9th grade.

A summary of the steps to create an index are listed below. See **?** for additional detail in calculation of a summary index.

1. Switch signs where necessary so the positive direction indicates a larger outcome effect.
2. Demean outcomes and convert to effect sizes by dividing by its control group standard deviation.
3. Define groupings of outcomes.
4. Create a new variable that is a weighted average of the outcomes in each grouping. When constructing the weighted average, weight each element by the inverse of the covariance matrix of the standardized outcomes in each group.
5. Regress the new weighted average for each group on intervention status to estimate treatment effects.

C. Appendix Tables

Table A1: Means of education and behavior outcomes

	All Students	Lead Tested	BLL 5-9μg/dL	BLL ⩾10μg/dL
Blood lead level (μg/dL)	4.144	4.220	6.169	13.129
	(3.115)	(3.236)	(1.245)	(7.900)
Education Outcomes				
Reading Test Score (avg 3-5th grade)	−0.030	−0.204	−0.364	−0.474
	(0.965)	(0.956)	(0.934)	(0.916)
Math Test Score (avg 3-5th grade)	−0.033	−0.205	−0.366	−0.427
	(0.973)	(0.953)	(0.921)	(0.918)
Repeat a grade (grades 1-5)	0.046	0.102	0.133	0.140
	(0.210)	(0.303)	(0.339)	(0.347)
Reading Test Score (avg 6-8th grade)	−0.033	−0.174	−0.335	−0.409
	(0.967)	(0.952)	(0.932)	(0.920)
Math Test Score (avg 6-8th grade)	−0.038	−0.175	−0.324	−0.378
	(0.969)	(0.935)	(0.888)	(0.888)
Repeat a grade (grades 6-9)	0.101	0.142	0.193	0.197
	(0.302)	(0.349)	(0.395)	(0.398)
Adolescent Antisocial Behavior Outcomes				
Total Days Suspended from School (6th-10th grade)	4.34	8.49	11.29	14.35
	(13.39)	(19.85)	(22.88)	(26.75)
Total Days Absent (6th-10th grade)	20.78	30.64	37.23	41.31
	(31.00)	(39.30)	(45.74)	(47.65)
Total School Reported Crimes/Incidents (6th-10th grade)	0.93	1.96	2.44	2.77
	(3.02)	(4.63)	(5.09)	(5.40)
Ever Arrested (age 16-18)	0.05	0.08	0.11	0.12
	(0.21)	(0.27)	(0.31)	(0.33)
Ever Arrested - Violent (age 16-18)	0.02	0.04	0.05	0.06
	(0.13)	(0.18)	(0.21)	(0.24)
Ever Arrested - Property (age 16-18)	0.02	0.04	0.05	0.06
	(0.14)	(0.19)	(0.22)	(0.24)
Observations	153,039	19,731	5,857	935

Means and standard deviations are reported above for Intervention and Control Groups. Standard errors are reported for the difference with * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Individuals are categorized by their first BLL test result for summary statistics by blood lead level results.

End-of-Grade Test scores for grades 3 through 8 are given mean zero and standard deviation of one based on NC state average test score.

All models restrict our sample to individuals born in 1997 or earlier in order to allow all individuals to reach age 16 by 2013.

Note: The mean blood lead level for All Students does not equal the mean blood lead level for the Lead Tested individuals since some students are not matchable to lead testing data.

Table A2: Means of demographic, housing, and neighborhood characteristics

	All Students	Lead Tested	BLL 5-9μg/dL	BLL ⩾10μg/dL
Background Characteristics				
Male	0.51	0.51	0.52	0.55
	(0.50)	(0.50)	(0.50)	(0.50)
Minority	0.49	0.60	0.69	0.70
	(0.50)	(0.49)	(0.46)	(0.46)
Stand Alone Residence	0.67	0.65	0.63	0.66
	(0.47)	(0.48)	(0.48)	(0.48)
Home Built pre 1978	0.43	0.65	0.72	0.74
	(0.49)	(0.48)	(0.45)	(0.44)
Past Lead Tests at a Home (mean μg/dL)	3.91	4.09	4.20	4.43
	(1.21)	(1.16)	(1.18)	(1.52)
Age at Blood Lead Test	2.12	2.20	2.15	1.89
	(1.50)	(1.53)	(1.42)	(1.26)
Mother Education (years)	13.28	12.69	12.33	12.08
	(2.48)	(2.52)	(2.44)	(2.40)
Birth Weight (ozs)	115.81	113.52	112.54	111.22
	(21.86)	(21.95)	(21.39)	(20.56)
CBG Population Density (000s/sq mile)	2.56	3.04	3.15	3.11
	(2.10)	(2.14)	(2.14)	(1.95)
CBG Median HH Income	54.47	44.69	40.69	40.32
	(25.11)	(22.79)	(20.74)	(20.52)
CBG Percent in Poverty	0.26	0.40	0.46	0.48
	(0.30)	(0.40)	(0.42)	(0.43)
Observations	153,039	19,731	5,857	935

Means and standard deviations are reported above for Intervention and Control Groups. Standard errors are reported for the difference with * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Individuals are categorized by their first BLL test result for summary statistics by blood lead level results.

All information regarding housing or Census Block Group (CBG) 2000 neighborhood is based on address given at the time of the first lead test.

Table A3: Balancing test: Do observables predict an intervention?

	Intervention (10+)
Male	−0.004
	(0.058)
Minority	0.089
	(0.081)
Home Built pre 1978	0.126*
	(0.069)
Past Lead Tests at a Home (mean µg/dL)	−0.029
	(0.031)
Stand Alone Residence	−0.019
	(0.065)
Age at Blood Lead Test	0.020
	(0.029)
Birth Weight (ozs)	0.001
	(0.002)
Mother Education (years)	0.019
	(0.014)
No Father Information (birth certificate)	−0.064
	(0.066)
CBG Percent in Poverty	−0.080
	(0.076)
CBG Population Density (000s/sq mile)	−0.000
	(0.014)
CBG Median HH Income	−0.000
	(0.002)
F-Stat (p-value)	0.365
Observations	301

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to arbitrary within-CBG correlation in parentheses.

Dependent variable: Indicator equal to one if individual received two tests $\geqslant$10µg/dL. The reported p-value at the bottom of each panel is the result of an F-test of joint-significance of all of the reported variables in a regression.

All regressions include birth year indicator and age at blood test indicator. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

Table A4: Balancing test for missing data indicators

School Information Missing	0.030
	(0.070)
Residential Information Missing	−0.055
	(0.096)
Birth Record Information Missing	−0.027
	(0.050)
F-Stat (p-value)	0.855
Observations	368

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

Dependent variable: Indicator equal to one if individual received two tests $\geqslant 10\,\mu g/dL$. The reported p-value at the bottom of each panel is the result of an F-test of joint-significance of all of the reported variables in a regression.

We include all lead tested individuals in our intervention and control groups. Coefficients on dummies for matching a lead observation to the CMS schools records (school missing), parcels records (parcels missing) and birth records (mother's education missing) indicate which lead observations are matched across these databases. We include but do not report dummies for birthyear and test age.

Table A5: Mobility

	(1) Moved after BLL test and before Starting School	(2) Did not Enroll Public Elementary	(3) Did not Enroll Public Middle or HS
Intervention	−0.069	0.035	−0.003
	(0.047)	(0.036)	(0.027)
Observations	324	368	368

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

Dependent variables: 1) *Moved after BLL test and before Starting School* is equal to one if an individual contains a different home address at time the time of BLL testing and the first year of public school. For cases when an individual never entered public school in Mecklenburg County, NC, we set the dependent variable to zero but include dummy for Did not Enroll if Public Elementary. This dependent variable loses 44 observations due to missing/non-geocodable address information at time of testing or while in school. 2)*Did not Enroll if Public Elementary* is equal to one if an individual enrolled in public school for at least one year of (1st through 5th grade). 3)*Did not Enroll if Public Middle/HS* is equal to one if an individual enrolled in public school for at least one year of (6th through 10th grade).

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, mother's education, single family home indicator, built pre 1978 indicator and Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

Table A6: Effects of an elevated BLL intervention on summary index outcomes: *Robustness Checks - Alternative Control Groups*

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Main Results (>10, 5-9)		
Intervention	0.112*	−0.161**
	(0.067)	(0.077)
Observations	301	301
Control = At least 1 test $\geqslant 10$		
Intervention	0.088	−0.170**
	(0.068)	(0.080)
Observations	577	577
Control = at least 1 test $\geqslant 5$		
Intervention	0.046	−0.148**
	(0.063)	(0.059)
Observations	7,155	7,155
Control = initial BLL of 15+		
Intervention	0.239	−0.200
	(0.158)	(0.169)
Observations	148	148
Control = initial BLL of 5 or less		
Intervention	−0.020	−0.084
	(0.067)	(0.073)
Observations	15,442	15,442
Control = two lead tests		
Intervention	0.051	−0.169***
	(0.063)	(0.062)
Observations	3,471	3,471

Control: $\geqslant$ 10, 5-9: Results for models using our preferred control group.

Control = At least 1 test $\geqslant 10$: Expands the definition of our control group to include observations with at least one BLL test of 10 or more.

Control = at least 1 test $\geqslant 5$: Expands the definition of our control group to include observations with at least one BLL test of 5 or more.

Control: initial BLL of 15+: These results present estimated effects from models that define the control group as those with initial BLL test results of 15µg/dL or more.

Control = initial BLL of 5 or less: These results present estimated effects from models that define the control group as those with initial BLL test results of 5µg/dL or less.

Control = two lead tests: These results present estimated effects from models that define the control group as those with at least 2 BLL tests of any value

Table A7: Effects of an elevated BLL intervention on summary index outcomes: *Robustness Checks II - Different Control Variables*

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Main Results (>10, 5-9)		
Intervention	0.112*	−0.161**
	(0.067)	(0.077)
Observations	301	301
Control for Test Type		
Intervention	0.106	−0.158**
	(0.070)	(0.078)
Observations	301	301
Initial BLL FE		
Intervention	0.064	−0.147
	(0.078)	(0.111)
Observations	301	301
Limited Control Variables		
Intervention	0.120	−0.197**
	(0.074)	(0.086)
Observations	301	301

Control for Test Type: These results incorporate our preferred control group and include a indicator for the type of BLL test used for a second (confirmatory) test.

Initial BLL FE: These results are for models that include fixed effects for the initial BLL test result. The fixed effect controls for selection concerns arising from parents responding differently to initial results by identifying results within initial BLL values.

Limited Control Variables: These results incorporate our preferred control group but exclude all control variables except year born and age of test and dummies for missing information for a grade.

All models as described in Table 6 except change noted.

Table A8: Falsification Test of Intervention using other BLL Thresholds

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
BLL=7		
False Intervention	−0.035	−0.043
	(0.095)	(0.083)
Observations	238	238
BLL=5		
False Intervention	−0.100	0.110*
	(0.065)	(0.058)
Observations	726	726
BLL=3		
False Intervention	−0.012	0.078
	(0.052)	(0.055)
Observations	1,049	1,049

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

This table presents our three different sets of results based on creating treatment and control groups around three different BLL thresholds below 10µg/dL. All results only include individuals with at least 2 BLL tests and constructing in similar ways to our main results. We limit to small intervals around these thresholds so that samples do not overlap between our different false thresholds as well as limit underlying differences in BLL exposure between treatment and control groups. For the BLL=7 threshold, we include individuals in the treatment group if they have two tests at 7-9µg/dL and the control group as one test 7-9µg/dL and one test 5-6µg/dL. For the BLL=5 threshold, we include individuals in the treatment group if they have two tests at 5-6µg/dL and the control group as one test 5-6µg/dL and one test 3-4µg/dL. For the BLL=3 threshold, we include individuals in the treatment group if they have two tests at 3-4µg/dL and the control group as one test 3-4µg/dL and one test below 3µg/dL. During the time period of our analysis, there was not a significant intervention associated with BLL tests over 5µg/dL even though currently the CDC recommends information interventions at this threshold.

Table A9: Effects of an elevated BLL intervention on summary index outcomes for siblings

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
All Siblings		
Sibling of Child (>10 , >10)	0.236*	−0.165
	(0.127)	(0.182)
Observations	138	138
Younger Siblings		
Younger Sibling of Child (>10 , >10)	0.057	−0.470
	(0.246)	(0.332)
Observations	74	74
Older Siblings		
Older Sibling of Child (>10 , >10)	0.363	−0.036
	(0.528)	(0.455)
Observations	43	43

The sample for this analysis is based only on siblings of our intervention and control group. We limit to only siblings within 3 years of age. Siblings are defined based on being born to the same mother (identified by first name, last name and date of birth). Results based off of 44 intervention siblings. All results based on the use of a broader control group of siblings, defined by individuals whose first BLL test result was $\geqslant 10 \mu g/dL$.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

End-of-Grade Test scores for grades 3 through 8 are given mean zero and standard deviation of one based on NC state average test score.

All models restrict our sample to individuals born in 1997 or earlier in order to allow all individuals to reach age 16 by 2013.

Table A10: Regression Discontinuity Results

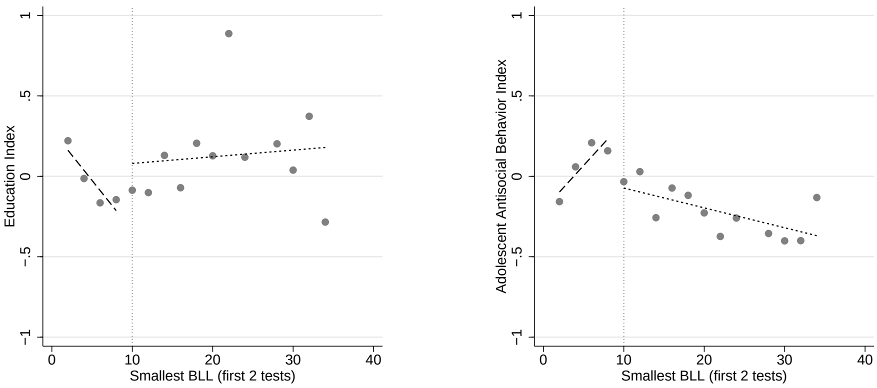
	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Observations with 2 tests (minimum $5 \leqslant \text{BLL} \leqslant 15$)		
Intervention	0.016	−0.119
	(0.351)	(0.257)
Observations	313	313
Main Sample (1 test $\geqslant 10$, 1 test $\geqslant 5$)		
Intervention	0.142	−0.173
	(0.356)	(0.260)
Observations	301	301

* p < 0.1, ** p < 0.05, *** p < 0.01. Standard errors robust to arbitrary within-CBG correlation in parentheses.

All regressions include controls for gender, minority, birth year indicator, average previous lead levels for prior households in the home, age at blood test indicator, an indicator for low birth weight, parental education, single family home indicator, built pre 1978 indicator, and indicators if an individual was missing school information for the grades upon which we measure a given dependent variable. All regressions also include Census Block Group 2000 variables for median household income, percent of families in poverty and population density. Since variables for parent's education, CBG attributes and housing attributes contain missing values in some cases, we include a dummy for missing value for each of these variables and replace the variable equal to zero if missing.

The top panel presents results from a regression discontinuity design (RDD) using a sample of individuals that had two BLL tests. As the running variable, we use the minimum BLL among the first two tests, a bandwidth of 5µg/dL (5µg/dL⩽minimum BLL⩽15µg/dL) and the best fitting polynomial for the data on each side of the BLL=10µg/dL threshold. The bottom panel of results implements a RDD design similar to the top panel but instead uses the second confirmatory test result as the running variable and expands the bandwidth to include all observations from our estimation sample.

Figure A1: Regression Discontinuity Plots



These plots include all individuals with two BLL tests and uses the minimum BLL as the running variable on the horizontal access. The sample used in these plots corresponds to the sample used in the top panel of results in the table above, but the results above only use data within the window 5µg/dL⩽minimum BLL⩽15µg/dL.

Figure A2: Elevated blood lead level intervention policy of the Children's Environmental Health branch within the North Carolina Department of Health

Interpretation of Screening Test Results and Recommended Follow-up

Blood Lead Level (μg/dL)	**Comments**
<10	A child with this Blood Lead Level (BLL) is not considered to have an elevated level of exposure. Reassess or rescreen in one year. No additional action is necessary unless exposure sources change.
10-14	The CDC considers 10 μg/dL to be a level of concern. Perform diagnostic test on venous blood within three months. If the diagnostic test is confirmatory, the child should have follow-up tests at three month intervals until the BLL is <10 μg/dL. Provide family lead education. Refer for nutrition counseling.
15-19	A child in this category should also receive a diagnostic test on venous blood within three months. If the diagnostic test is confirmatory, the child should have additional follow-up tests at three month intervals. Children with this level of exposure should receive clinical management. Parental education and nutritional counseling should be conducted. A detailed environmental history should be taken to identify any obvious sources of lead exposure.
20-44	A child with a BLL in this range should receive a confirmatory venous test within one week to one month. The higher the screening test, the more urgent the need for a diagnostic test. If the diagnostic test is confirmatory, coordination of care and clinical management should be provided. An abdominal x-ray is completed if particulate lead ingestion is suspected. Nutrition and education interventions, a medical evaluation, and frequent retesting (every 3 months) should be conducted. Environmental investigation and lead hazard control is needed for these children.
45-69	A child in this category should receive a confirmatory venous test within 48 hours. If the screening blood lead level is between 60-69 μg/dL, the child should have a venous blood lead level within 24 hours. If confirmatory, case management and clinical management should begin within 48 hours. Environmental investigation and lead hazard control should begin as soon as possible. A child in this exposure category will require chelation therapy and an abdominal x-ray is completed if particulate lead ingestion is suspected.
≥70	A child with a BLL ≥70 requires immediate hospitalization as lead poisoning at this level is a medical emergency. Confirmatory venous testing should be done as soon as possible. An abdominal x-ray is completed if particulate lead ingestion is suspected and chelation therapy should begin immediately. Case and clinical management including nutrition, education, medical and environmental interventions, must take place as soon as possible.

Information from Centers for Disease Control and Prevention. Screening Young Children for Lead Poisoning: Guidance for State and Local Public Health Offices. November 1997. Atlanta, Georgia. United States Department of Health and Human Services, Public Health Services, CDC, 1997 and Centers for Disease Control and Prevention. Managing Elevated Blood Lead Levels Among Children: Recommendations from the Advisory Committee on ChildhoodLead Poisoning Prevention. March 2002

Figure Note: This guide represents NC Health Department Policies in 2002 (entirely based on CDC recommendations). Since some of our sample is tested prior to 2002, we have investigated and found no changes in lead policy in the years preceding. Conversations with the NC Childhood Lead Poisoning Prevention Program have confirmed that these guidelines were used at least back to 1991. Based on conversations with health workers in North Carolina and specifically Mecklenburg County, NC, along with inspection of the recommended interventions, the thresholds for which policy is substantially different is the 10μg/dL and the 20μg/dL threshold. We add emphasis of interventions triggered by underlining the intervention components (excluding further testing).