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

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NON-TECHNICAL SUMMARY

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 primarily due to lead-based paint hazards in older housing. As is the case with other environmental threats, 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 long-term outcomes, the U.S. Center for Disease Control (CDC) recommends blood lead testing for children around one and two years of age as well as 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 in the environment through information and remediation as well as provide additional health and public assistance benefits for lead-poisoned children. Since the CDC lowered the alert threshold to 10 micrograms of lead per deciliter of blood in 1991, millions of children in the United States have been eligible for the early-life health and environmental treatments following test results showing elevated level of lead in the blood. 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.

We merge blood lead surveillance data, public school records, and criminal arrest records at the individual level to evaluate the long-term impact of these public health actions triggered by BLLs over the alert threshold on school performance and adolescent behavior in Charlotte, North Carolina. We identify the impact of intervention based on the fact that individuals with two consecutive tests over the alert threshold are eligible for intervention whereas individuals with an initial test over this threshold and a subsequent test just under the threshold are not. Consistent with a growing literature that finds profound impacts from early-childhood health interventions on long-term cognitive and behavioral outcomes, we find that interventions triggered by elevated blood lead levels significantly reduce adolescent antisocial behavior and increase academic achievement. The magnitudes of our estimates suggest that the behavioral and educational impairments previously associated with early-life lead exposure can largely be reversed by the intervention.

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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 behavioral and education deficits previously associated with early-life exposure can largely be reversed by intervention.

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

JEL classification codes: I12, I18, I21, J13, J24, K42, Q53, Q58

1. Introduction

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. Jacobs et al. (2002) estimate that approximately one out of every four homes in the United States contains a significant lead paint hazard. Lead exposure has been labeled the "single most significant health threat" to children by the Natural Resources Defense Council (Mott et al., 1997) and "among the broadest and longest lasting [epidemics] in American public health history" (Rosner and Markowitz, 2012). 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 (Aizer and Currie, 2014).

Given the large body of evidence connecting childhood lead exposure to cognitive and behavioral deficiencies,[1] 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, North Carolina.[2] 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 $\text{BLL} \geqslant 10\mu\text{g/dL}$) and control group (first test with $\text{BLL} \geqslant 10\mu\text{g/dL}$ and second test with $5\mu\text{g/dL} \leqslant \text{BLL} < 10\mu\text{g/dL}$). 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.[3]

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[1] EPA (2013) 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 (EPA, 2013).

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

[3] 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 (ATSDR, 2007;

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 is triggered by two tests over 20µg/dL. In addition to educating caregivers and providing a referral to remediation services, the intensive intervention can include: 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 decrease in antisocial behavior and an increase in educational performance among individuals whose BLL test results trigger an intervention. Relative to our control group, we estimate a 0.179 standard deviation decrease in antisocial behavior and a 0.128 increase in educational performance among children eligible for an intervention several years before school entry.[4] For the intensive intervention at the 20µg/dL threshold, we estimate a 0.382 standard deviation decrease in antisocial behavior and a 0.368 standard deviation increase in educational performance relative to the control group. These estimates are large in magnitude. In fact, the negative effects of high levels of exposure on antisocial behavior and educational performance 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<5µg/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.[5] 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.

Kemper et al., 2005; CDC, 1997). Moreover, blood lead tests do not measure cumulative exposure since the elimination half-lives for inorganic lead in blood is approximately 30 days (ATSDR, 2007).

[4] 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 (Anderson, 2008).

[5] Since the CDC began collecting national statistics on blood lead surveillance in 1997, nearly one million children were confirmed to have elevated BLLs (BLL>10µg/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.

Second, this paper contributes to a growing literature evaluating the causal impact of early-childhood health interventions on long-term cognitive and behavioral outcomes (Cunha and Heckman, 2008; Currie and Almond, 2011). Recent research suggests that early health and education interventions can yield large long-term benefits.[6] 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 (Barnett and Masse, 2007; Anderson, 2008; Campbell et al., 2014). Many other early-life interventions have also proven effective, such as those administering increased medical care at birth (Bharadwaj et al., 2013); nutritional supplementation for pregnant women and young children (Hoynes et al., 2011); nurse home visit programs (Olds et al., 1999, 2007); and high-quality preschool programs such as Perry Preschool and Head Start (Currie and Almond, 2011; Heckman et al., 2013; Bitler et al., 2014; Conti et al., 2015). The elevated BLL 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 (Reyes, 2015; Clay et al., 2014; Grønqvist et al., 2014; Rau et al., 2013; Ferrie et al., 2012; Reyes, 2011; Nilsson, 2009; Troesken, 2008; Reyes, 2007). 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).[7]

We cannot separately identify these two mechanisms or estimate the effects of specific elements

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[6] See Currie and Almond (2011) for a recent review.

[7] 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 Bharadwaj et al. (2013)); increased access to medical professionals (e.g. the Nurse-Family Partnership evaluated by Olds et al. (2007)); improved early-life nutrition and increased access to public assistance programs (Hoynes et al., 2011, 2012); high-quality early childcare and preschool programs which focus on these social and cognitive developmental processes (e.g. Abecedarian, Perry Preschool, and Head Start).

of these elevated BLL intervention packages separately.[8] 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 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 (Budtz-Jørgensen et al., 2013; CDC, 2012).[9] 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.[10]

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.

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

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[8] 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 (Campbell et al., 2014); Bharadwaj et al. (2013) find long-term effects from a "bundle of medical interventions" triggered by a very low birth weight threshold.

[9] 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.

[10] Cost benefit analyses of early-life intervention programs find a 4 to 1 return for Abecedarian (Masse and Barnett, 2002) and a 7 to 1 return associated with Perry Preschool (Karoly et al., 1998).

reduce childhood exposure (Meyer et al., 2003). 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 (CDC, 1991).[11]

The NC Childhood Lead Poisoning Prevention Program of the Children’s Environmental Health Branch bases intervention policies and procedures on CDC recommendations.[12] 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.[13] Figure A1 documents CDC recommendations as of 2002. Based on conversations with health workers in Mecklenburg County, NC, these CDC recommendations constituted public health policy in Charlotte back to 1991.[14]

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. Two tests over 20μg/dL 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. While we report heterogeneous intervention effects for children with BLLs$\geqslant$20μg/dL, we do not report heterogeneous effects for individuals with two tests of 15μg/dL$\leqslant$BLL$<$20μg/dL despite the fact that 15μg/dL is listed as a separate threshold in Figure A1. According to health workers, interventions are only substantially different at the 20μg/dL threshold in practice. This discontinuity is also evident in Figure A1: the majority of interventions continue to be based on information and education at the 15μg/dL threshold while more direct medical and remediation actions are emphasized at the 20μg/dL threshold.

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

[12] 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.

[13] The initial test is usually based on capillary specimens obtained by the “finger-prick method” where the follow-up test is often a procedure using venous blood, which is less likely to be contaminated. The NC Blood Lead Surveillance data indicate that approximately one-third of follow-up tests are venous during our sample period and the initial lead value is not predictive of the second test type indicating that the variation is likely due to resources available at the testing clinics.

[14] 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 most of our sample was tested for lead (1990-2000), the 5μg/dL threshold did not trigger any policy interventions.

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.[15]

Based on the environmental history interview or two consecutive tests over 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 $\$6,832$.[16]

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 (CDC, 1991). 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 two consecutive tests 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.

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[15] 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.

[16] 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.

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 born between 1990 and 1997 in Charlotte-Mecklenberg County, NC.[17] Blood lead surveillance data are maintained by the NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch.[18] This dataset includes BLL test results, which allow us to determine which children received various lead policy interventions due to two tests with BLLs of 10µg/dL or above.[19] While the majority of tested individuals have low BLL levels, a sufficient number of tests indicate BLLs over our threshold of interest—the 10µg/dL requirement for policy intervention.

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.[20] 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.[21]

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.[22] 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.

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

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

[18] 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.

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

[20] We are able to match 65% of lead tests to a student record in CMS. This match rate improves to 74% for our main sample of individuals with two tests and one test>10µg/dL.

[21] 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.

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

education.[23] 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.[24]

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). Benefits from intervention are also evident from many of the panels of Figure 2, which display mean outcomes for each integer level of initial BLL result as well as mean outcomes for the control group and intervention groups.

Given that our ability to match lead data ranges from 54% to 86%, we are concerned that matches may be related to demographics or parental factors. Names from certain ethnic groups may have lower match rates 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 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.

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[23] We are able to match approximately 54% 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.

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

4. Empirical Framework

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

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

where Y_i is an outcome for individual i and $\mathbf{X}_i$ includes a wide range of controls.[25] Each outcome is regressed on an indicator, $\mathtt{Intervention}_i$, 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.

We also allow for heterogeneous effects based on the intensity of intervention by splitting $\mathtt{Intervention}_i$ and estimating the following model:

$$Y_i = \alpha_1 \mathtt{Intervention}_i^{(10-19)} + \alpha_2 \mathtt{Intervention}_i^{(20+)} + \mathbf{X}_i \beta + \epsilon_i \tag{2}$$

where $\mathtt{Intervention}_i^{(10-19)}$ is equal to one if child i has two BLL test results $\geqslant$10μg/dL with at least one test <20μg/dL; and $\mathtt{Intervention}_i^{(20+)}$ is equal to 1 for those with two tests above 20μg/dL. Interventions differ between these two groups as indicated by Figure A1 and Eq. (2) allowing for separate effects of the higher intensity interventions triggered by the 20μg/dL threshold.

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 Anderson (2008) in a re-evaluation of several early childhood intervention programs.[26] 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.[27] We also estimate and present results separately for individual outcomes

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[25] 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.

[26] The steps to calculate the summary index are outlined in detail in Anderson (2008). We also provide a description of the steps in the Appendix.

[27] 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

used in the summary indexes.

Throughout the empirical analysis, we estimate Eq. (1) and Eq. (2) 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 a second 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 we are most interested in measuring the effects of the public health intervention net of effects from the information shock after an alarming initial test result. Moreover, the majority of individuals with an initial test above the threshold either do not return for a second test or achieve a second test result below the threshold. Precise estimates from a regression discontinuity design are also difficult given multiple intervention thresholds as well as a small number of observations near each of the thresholds.

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 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 (ATSDR, 2007; Kemper et al., 2005; CDC, 1997). First, BLL levels are influenced by the relationship between date of exposure (which is unknown to the family) and the date of testing with only a month of passed time generating over a 50% 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 other testing procedures. Other testing procedures, such as measuring lead in children's teeth, are much more accurate but also much more expensive and therefore less prevalent.[28]

Consistent with these characteristics of testing, we observe a great deal of variation in test results in our sample. The first panel of Figure 1 plots 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. The second panel of Figure 1 displays the distribution of test results within individuals by illustrating the various combinations of the two BLL tests among all individuals with at least two tests. The

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and 18 years of age for many of the children receiving lead tests since 1992.

[28] 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 (ATSDR, 2007).

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.[29] This supports the notion that a significant component of testing variation is due to idiosyncratic measurement error; if 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.[30] 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.[31]

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.[32] 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, we check that our results are

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

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

[31] We also show balance on observables separately for two ranges of intervention ($10\mu g/dL \leqslant BLL \leqslant 19\mu g/dL$) and ($BLL \geqslant 20\mu g/dL$) in Appendix Table A3.

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

robust to models including flexible controls for BLL test results and 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.[33] 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 A1). 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 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

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[33] 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.

cognitive outcomes, including measures of educational performance (EPA, 2013).[34] Improvements in educational outcomes are also consistently linked to early-life health and education interventions (Currie and Almond, 2011). 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 statistically significant 0.128 standard deviation increase in educational performance associated with the elevated BLL intervention. While effects for early education outcomes (3rd through 5th grade) are imprecise, they are consistent with benefits from intervention.

Early-life lead exposure is linked to increases in behavioral problems, conduct disorders, and adult criminal activity (EPA, 2013).[35] Moreover, early-life childcare and nurse-family partnership interventions have been shown to reduce delinquent and criminal behavior among treated individuals (Currie and Almond, 2011). 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 0.179 standard deviation decrease in our antisocial behavior summary index associated 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 estimate much larger effects for the higher-intensity interventions. These effects are not statistically significant for all educational outcomes but are generally two or three times as big as the lower-level intervention, suggesting there may be large education benefits associated with the intensive intervention. Relative to our control group, Table 7 reports a 0.368 standard deviation increase in our educational performance index. We estimate a 0.382 standard deviation decrease in our antisocial behavior index associated with the set of interventions triggered by BLLs$\geqslant$ 20µg/dL, which is statistically significant at a 1 percent significance level.

Overall, these results suggest very large long-term educational and behavioral benefits from more intensive intervention. Estimated effects of the high-intensity intervention on education and behavior indexes are similar in magnitude to those found for the Abecedarian and Perry Preschool programs. Anderson (2008) reports around a 0.4 standard deviation effect on a

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[34] Effects are found across different measures of cognition and academic performance such as: IQ tests (Schnaas et al., 2006; Lanphear et al., 2005; Ris et al., 2004; Canfield et al., 2003; Bellinger et al., 1992), primary school assessments (Rau et al., 2013; McLaine et al., 2013; Zhang et al., 2013; Reyes, 2011; Chandramouli et al., 2009; Miranda et al., 2009; Nilsson, 2009; Miranda et al., 2007), high school graduation (Nilsson, 2009; Fergusson et al., 1997; Needleman et al., 1990), and even lower adult earnings (Nilsson, 2009). EPA (2013) reviews many other studies.

[35] Lead has been found to impact externalizing behaviors such as attention, impulsivity, and hyperactivity in young children (Froehlich et al., 2009; Chen et al., 2007). These behavioral effects translate to increased delinquent and antisocial activity (Reyes, 2015; Dietrich et al., 2001; Needleman et al., 1996) as well as higher rates of arrest (Reyes, 2015; Wright et al., 2008; Fergusson et al., 2008; Needleman et al., 2002). EPA (2013) reviews many other studies.

summary index from the Abecedarian intervention and similar effects for his re-evaluation of the Perry Preschool results. In our analysis, the largest benefits appear to emerge in late adolescence, which is also consistent with previous evaluations of early-life interventions. For example, in an evaluation of Head Start, Deming (2009) finds larger effects for young adult outcomes (including crime) than for primary school test scores.

We conduct several robustness checks in Appendix Table 5A. First, we show that our results do not depend on the specification of our primary control group (one test with BLL$\geqslant$10μg/dL and a second test with 5$\leqslant$BLL$<$10μg/dL). We obtain similar estimates to those presented in Table 6 for the following control groups: one test exceeding 10 and any second test under 10μg/dL; only individuals with one test over 10μg/dL who do not return for a follow-up test; all individuals with at least one test result yielding a BLL$\geqslant$5μg/dL; and only individuals with an initial test with BLL$\geqslant$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 A6. 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.

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 A7 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. Are Benefits Due to Reductions in Exposure?

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. The recommended intervention, especially at high detected lead levels involves an increase in the early-life presence of public agencies through activities such as monitoring and assessing early-life health and development as well as through the provision of public assistance.

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 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 (Sandel et al., 2010) and the number of elevated BLL cases (Jones, 2012). 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 8 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 9 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.

Results from models allowing for heterogeneous intervention effects by the intensity of intervention suggest that intervention elements which require a response by a public agency (medical/developmental evaluation, mandatory home investigation, and nutritional intervention) yield larger benefits compared with elements more focused on the provision of information to parents. Previous randomized control trials evaluating parental education interventions generally do not find large or significant BLL reductions (Campbell et al., 2011; Yeoh et al., 2009; Brown et al., 2006; Jordan et al., 2003; Lanphear et al., 1999).[36] Table 7 reports estimated effects for this type of intervention more than twice as large as an informational intervention.

Based on interviews with health workers in Charlotte, the 20µg/dL intervention is also likely associated with increased participation in WIC and possibly other forms of public assistance (such as "food stamps"). The higher-intensity intervention often includes a medical examination that pays particular attention to psycho-social and language development. Any deficiencies identified in this examination trigger referrals to appropriate services. Overall, the intense level of intervention is associated with increased involvement of public agencies and participation in public assistance programs. Unfortunately, we are not able to directly measure these responses. While our results separately estimating different levels of the intervention are limited by a smaller number of treated observations, we report improvements in education and behavioral outcomes, which are large and statistically significant. These results suggest programs that increase participation and involvement of public agencies yield wide-ranging benefits and are consistent with prior evaluations of early-life programs.

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[36] See Yeoh et al. (2009) for a systematic review of these evaluations. Yeoh et al. (2009) concludes "there is no evidence that educational and dust control interventions are effective in reducing BLLs in children."

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 increases in educational performance. These results support recent evidence that early-life interventions can have substantial long-term effects on behavioral outcomes, suggesting that these 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.[37] 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), randomized evaluations of public health responses to elevated BLLs may be difficult to implement due to ethical concerns. In fact, a randomized control trial investigating partial lead paint abatement procedures in Baltimore by researchers at Johns Hopkins University led to a controversial case questioning the ethics of experimental evaluations in a public health setting (Buchanan and Miller, 2006). However, 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 (Dixon et al., 2009; Gaitens et al., 2009; Levin et al., 2008). 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 (Jacobs et al., 2002). Recognizing the current 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 (Kleinberg, 2014).[38]

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[37] Recent media articles Drum (2013) and Monbiot (2013) highlight this connection based on results from papers by Mielke and Zahran (2012); Nevin (2007); Reyes (2007); Nevin (2000).

[38] 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.

Until 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 (CDC, 2012).[39] 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.

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[39] 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 Budtz-Jørgensen et al. (2013).

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

	Intervention	Control	Difference
Blood lead level (μg/dL)	17.85	11.77	6.08^{***}
	(8.25)	(4.50)	(0.72)
Education Index	0.09	−0.05	0.14^{*}
	(0.61)	(0.71)	(0.08)
Reading Test Score (avg 3-5th grade)	0.44	−0.59	0.15
	(0.83)	(0.90)	(0.11)
Math Test Score (avg 3-5th grade)	−0.46	−0.52	0.06
	(0.81)	(0.93)	(0.11)
Repeat a grade (grades 1-5)	0.15	0.15	0.00
	(0.36)	(0.36)	(0.04)
Reading Test Score (avg 6-8th grade)	−0.32	−0.52	0.20^{*}
	(0.81)	(0.94)	(0.12)
Math Test Score (avg 6-8th grade)	−0.31	−0.46	0.15
	(0.82)	(0.87)	(0.11)
Repeat a grade (grades 6-9)	0.14	0.22	−0.07
	(0.35)	(0.41)	(0.05)
Adolescent Antisocial Behavior Index	−0.16	0.10	-0.26^{***}
	(0.47)	(0.83)	(0.08)
Total Days Suspended (6th-10th grade)	9.25	17.80	-8.55^{***}
	(15.80)	(31.96)	(3.14)
Total Days Absent (6th-10th grade)	30.61	47.01	-16.41^{***}
	(36.31)	(54.54)	(5.64)
Total School Reported Crimes (6th-10th grade)	1.97	3.49	-1.51^{**}
	(3.40)	(6.66)	(0.66)
Ever Arrested	0.08	0.18	-0.10^{**}
	(0.27)	(0.38)	(0.04)
Ever Arrested - Violent	0.03	0.11	-0.08^{***}
	(0.16)	(0.31)	(0.03)
Ever Arrested - Property	0.04	0.08	−0.03
	(0.20)	(0.27)	(0.03)
Observations	119	193	312

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 Anderson (2008) 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 based on 3rd through 8th grades and 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	0.03
	(0.49)	(0.50)	(0.06)
Minority	0.77	0.78	−0.01
	(0.42)	(0.41)	(0.05)
Stand Alone Residence	0.58	0.58	−0.01
	(0.50)	(0.49)	(0.06)
Home Built pre 1978	0.79	0.78	0.01
	(0.41)	(0.42)	(0.05)
Past Lead Tests at a Home (mean µg/dL)	4.40	4.49	−0.09
	(1.16)	(1.50)	(0.25)
Age at Blood Lead Test	1.81	1.71	0.10
	(1.34)	(1.12)	(0.14)
Father Education (years)	12.31	12.55	0.23
	(2.63)	(2.27)	(0.45)
Mother Education (years)	11.92	11.49	0.43
	(2.96)	(2.30)	(0.36)
Birth Weight (ozs)	115.09	109.94	−5.15
	(20.37)	(21.49)	(3.01)
CBG Population Density (000s/sq mile)	3.30	3.25	0.06
	(2.06)	(2.19)	(0.25)
CBG Median HH Income	38.78	36.63	2.15
	(22.25)	(17.38)	(2.26)
CBG Percent in Poverty	0.48	0.55	−0.07
	(0.41)	(0.47)	(0.05)
F-stat (p-value)			0.725
Observations	119	193	312

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 $\geqslant 10\mu g/dL$ and a second test $\geqslant 5\mu g/dL$ but $< 10\mu g/dL$.

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	0.029	0.003
	(0.048)	(0.046)
Observations	1,375	1,375

* 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 Anderson (2008) 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	0.538^{***}	2.639^{***}	-7.498^{***}	0.072^{**}
	(0.041)	(0.279)	(1.377)	(0.032)
Dep. Var. (mean) for Control Group	0.20	2.31	11.62	0.03
Observations	380	380	136	380

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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	0.128^{**}	0.174	0.106	0.028	0.200^{**}	0.150^{*}	-0.053
	(0.064)	(0.120)	(0.108)	(0.040)	(0.097)	(0.086)	(0.043)
Observations	312	251	255	312	246	247	312

	(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	-0.179^{**}	-5.502^{**}	-9.466^{**}	-1.170^{*}	-0.072	-0.061^{**}	-0.022
	(0.080)	(2.460)	(3.983)	(0.595)	(0.045)	(0.030)	(0.038)
Observations	312	312	312	312	312	312	312

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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 Anderson (2008) 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 based on 3rd through 8th grades and 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: Effects of an elevated BLL intervention on education and behaviorial outcomes by intensity of intervention

	(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 (20+)	0.368^{***}	0.483^{***}	0.251	0.025	0.595^{***}	0.274	−0.071
	(0.138)	(0.173)	(0.170)	(0.078)	(0.179)	(0.169)	(0.084)
Intervention (10-19)	0.064	0.063	0.056	0.029	0.076	0.112	−0.048
	(0.071)	(0.128)	(0.120)	(0.045)	(0.099)	(0.093)	(0.047)
Observations	312	251	255	312	246	247	312

	(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 (20+)	-0.382^{***}	-9.295^{**}	-16.873^{***}	-2.641^{***}	-0.161^{***}	-0.114^{***}	-0.064^{**}
	(0.093)	(3.956)	(6.308)	(0.772)	(0.043)	(0.036)	(0.028)
Intervention (10-19)	−0.127	-4.533^{*}	-7.575^{*}	−0.794	−0.049	−0.048	−0.011
	(0.088)	(2.487)	(4.553)	(0.630)	(0.050)	(0.033)	(0.044)
Observations	312	312	312	312	312	312	312

* 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 based on 3rd through 8th grades and 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.

We split our intervention indicator ("Intervention") into two categories: Individuals who receive a test result indicating BLL⩾20µg/dL and thus a more intensive intervention; and those who have two tests with 10⩽BLL<20 and receive a less intensive intervention. Individuals exceeding the 20µg/dL threshold receive an intervention involving more intensive case management, medical evaluations, and nutritional interventions whereas children testing between 10-19µg/dL receive an intervention primarily focused on the provision of information about lead exposure reduction and nutrition.

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

Table 8: Heterogeneous Effects of Intervention

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Intervention*Large Drop in BLL	0.075	-0.202^{*}
	(0.147)	(0.103)
Intervention	0.109	−0.127
	(0.066)	(0.088)
Observations	312	312
Intervention*Quick Time to Next BLL Test	0.099	−0.063
	(0.155)	(0.108)
Intervention	0.116^{*}	-0.172^{**}
	(0.066)	(0.079)
Observations	312	312

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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 Anderson (2008) 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.

We define quick time between 2nd and 3rd test based on less than 1 month between 2nd (confirmatory) test and a 3rd BLL test. We define large drop as those individuals that see a drop in BLL of more than 5 BLL between 2nd and 3rd test. Coefficients on interaction terms indicate heterogenous effects for treatment group based on time between tests or drop in BLL.

Table 9: 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	0.055	0.062	0.006	−0.010	0.086	0.009	−0.020
	(0.075)	(0.096)	(0.093)	(0.035)	(0.117)	(0.112)	(0.042)
Observations	435	352	355	435	339	339	435

	(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	−0.100	−1.368	−1.286	−0.180	-0.062^{**}	-0.031^{**}	-0.050^{**}
	(0.092)	(2.484)	(4.934)	(0.693)	(0.025)	(0.014)	(0.020)
Observations	435	435	435	435	435	435	435

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

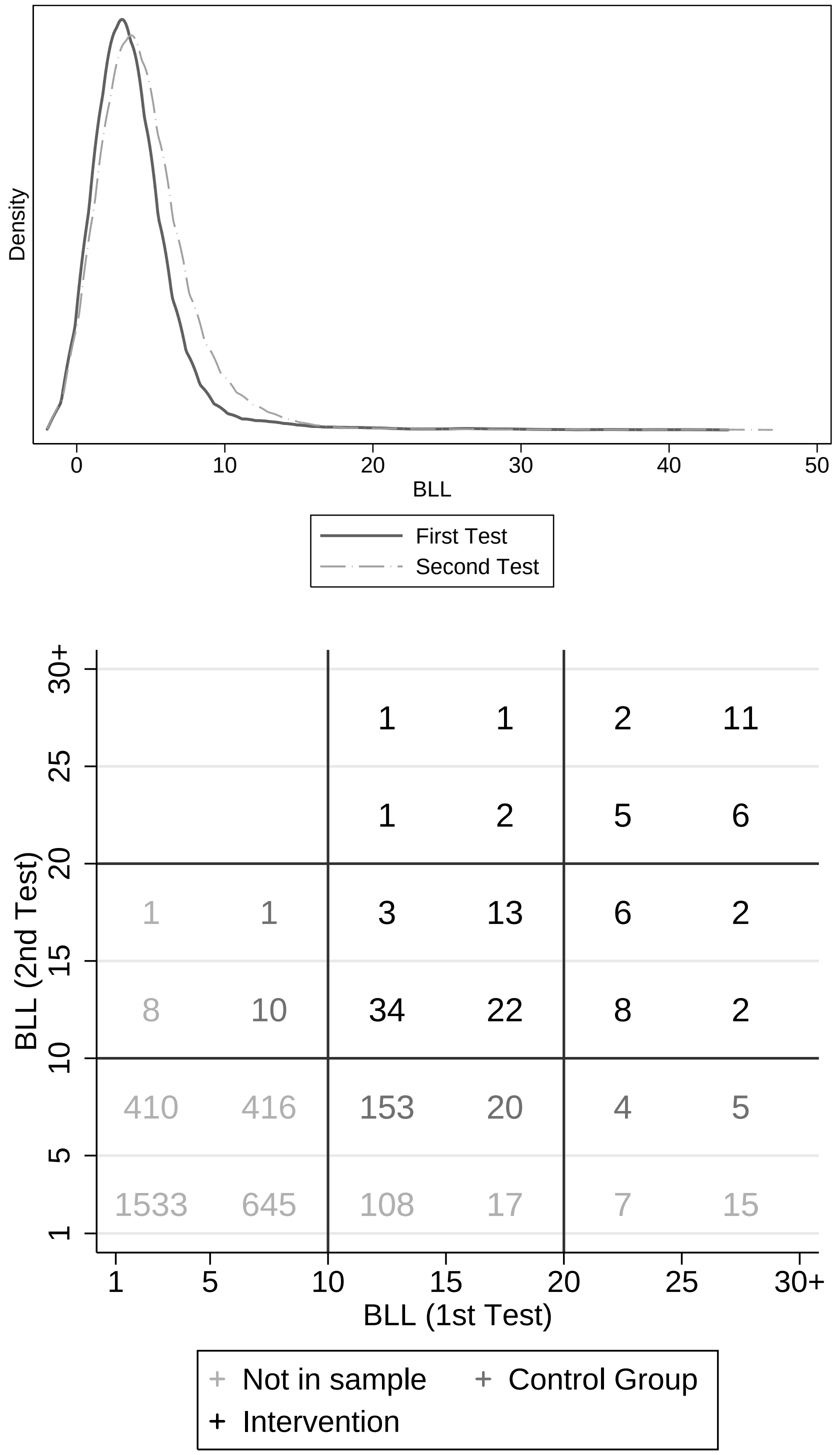
We follow the methodology for creating a summary index as outlined in Anderson (2008) in a re-evaluation of several early childhood intervention programs. Each summary index is a weighted mean of standardized outcomes. The education index includes 3rd through 5th grade math and reading test score results 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 based on 3rd through 8th grades and 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.

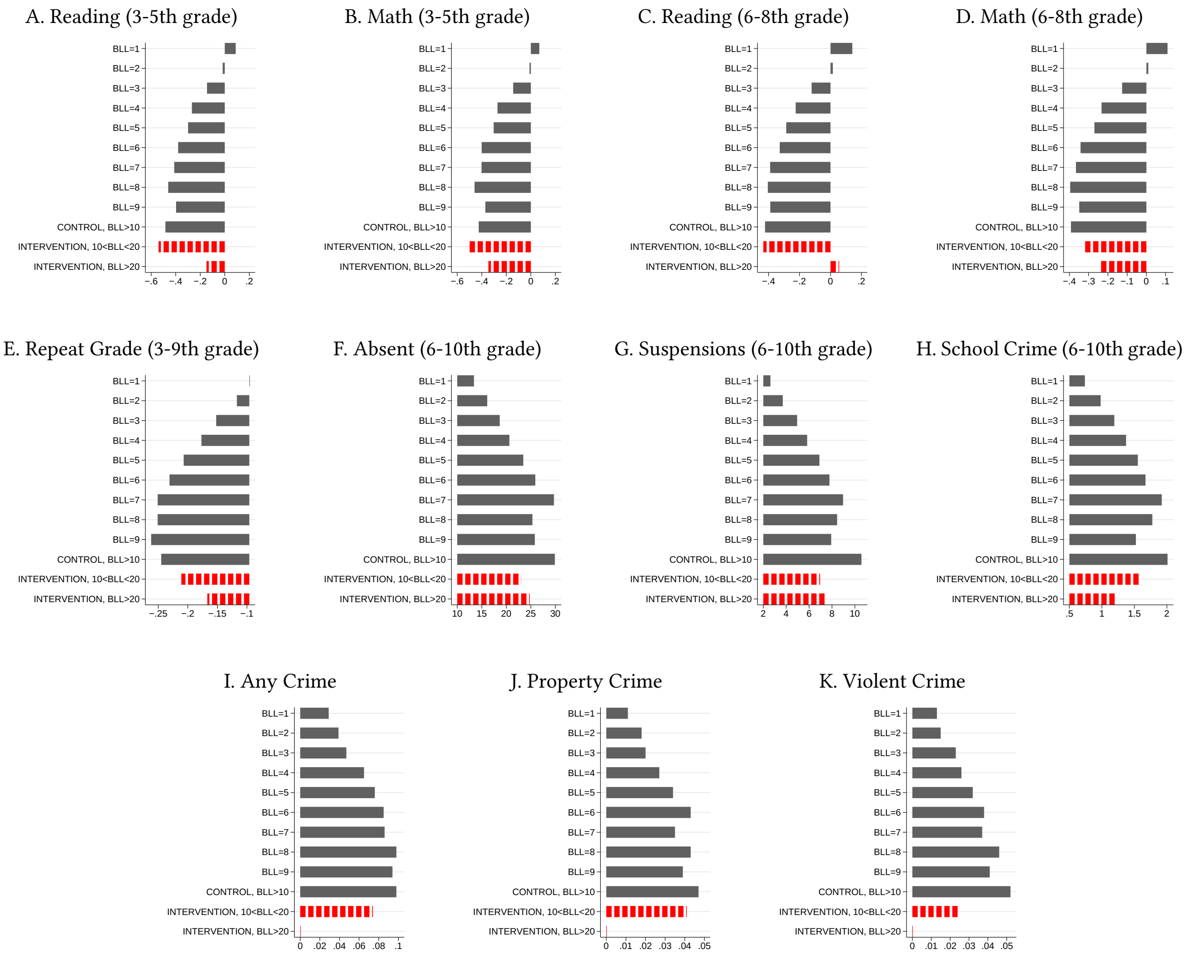
The sample used in this table is based on individuals that lived at the same address *after* our sample of treatment and control observations. We also drop any parcels that contain both treatment and control observations.

Figure 1: Blood Lead Testing Variation



The top figures provides the distribution of first and second BLL tests for the full blood surveillance dataset. This figure plots the relationship between 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 2: Average Outcomes by Blood Lead Level


A. Reading (3-5th grade)

B. Math (3-5th grade)

C. Reading (6-8th grade)

D. Math (6-8th grade)

E. Repeat Grade (3-9th grade)

F. Absent (6-10th grade)

G. Suspensions (6-10th grade)

H. School Crime (6-10th grade)

I. Any Crime

J. Property Crime

K. Violent Crime

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

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% 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.[40] We are able to match 65 % of lead tests to a student record in CMS. This match rate improves to 74% 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% of the matches are exact, we recover additional matches

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[40] 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.

using an algorithm for partial matches that has been used and validated in Deming (2011). 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% 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 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% 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.

A.1. Summary Index Construction

We follow the methodology in Anderson (2008) 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 Anderson (2008) 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.

Table A1: Means of education and behavior outcomes

	All Students	Lead Tested	BLL 5-9μg/dL	BLL $\geqslant$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 based on 3rd through 8th grades and 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 $\geqslant$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)
Father Education (years)	13.83	13.33	13.08	12.83
	(2.40)	(2.49)	(2.34)	(2.46)
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?

	(1) Intervention (10+)	(2) Intervention (10-19)	(3) Intervention (20+)
Male	0.019	0.047	−0.063
	(0.056)	(0.055)	(0.047)
Minority	0.046	−0.009	0.116*
	(0.077)	(0.075)	(0.061)
Home Built pre 1978	0.107	0.130*	0.012
	(0.067)	(0.067)	(0.062)
Past Lead Tests at a Home (mean µg/dL)	−0.023	−0.022	−0.017
	(0.031)	(0.032)	(0.024)
Stand Alone Residence	−0.032	−0.000	−0.051
	(0.068)	(0.075)	(0.062)
Birth Weight (ozs)	0.000	−0.001	0.002
	(0.001)	(0.001)	(0.001)
Father Education (years)	−0.003	−0.013	0.020
	(0.023)	(0.022)	(0.024)
Mother Education (years)	−0.005	0.001	−0.010
	(0.013)	(0.014)	(0.011)
CBG Percent in Poverty	−0.099	−0.056	−0.069
	(0.074)	(0.071)	(0.066)
CBG Population Density (000s/sq mile)	0.002	−0.009	0.013
	(0.015)	(0.013)	(0.013)
CBG Median HH Income	0.000	0.001	−0.000
	(0.002)	(0.002)	(0.002)
F-Stat (p-value)	0.725	0.385	0.498
Observations	312	288	217

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

Dependent variable: Indicator equal to one if individual received two tests $\geqslant$10µg/dL in column 1; an indicator based on two tests $\geqslant$10µg/dL, but at least one test between 10-19µg/dL in column 2; and an indicator based on 2 tests $\geqslant$20µg/dL in column 3. For column 2, we drop all observations with 2 tests $\geqslant$20µg/dL. For column 3, we drop all observations with two tests $\geqslant$10µg/dL, but at least one test between 10-19µg/dL.

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

	(1) Intervention (10+)	(2) Intervention (10-19)	(3) Intervention (20+)
School Information Missing	0.040	0.072	−0.053
	(0.070)	(0.069)	(0.047)
Residential Information Missing	−0.045	−0.037	−0.042
	(0.095)	(0.080)	(0.064)
Birth Record Information Missing	−0.021	−0.031	0.015
	(0.049)	(0.050)	(0.037)
F-Stat (p-value)	0.865	0.638	0.692
Observations	380	353	259

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

In these results, 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 and father'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 5A: Effects of an elevated BLL intervention on summary index outcomes: *Robustness Checks*

Intervention Estimate	Education Index	Adolescent Antisocial Behavior Index
Control = >10, 5-9	0.128^{**}	-0.179^{**}
	(0.064)	(0.080)
Observations	312	312
Control = >10, 1-9	0.111^{*}	-0.193^{***}
	(0.057)	(0.069)
Observations	468	468
Control = Only one test >10	0.095	-0.166^{**}
	(0.065)	(0.079)
Observations	577	577
Control = at least 1 test >=5	0.053	-0.147^{**}
	(0.063)	(0.061)
Observations	7,183	7,183
Control = initial BLL of 15+	0.154	-0.203^{*}
	(0.114)	(0.120)
Observations	202	202
Initial BLL FE	0.078	−0.139
	(0.081)	(0.118)
Observations	312	312

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

Control: ⩾ 10, 5-9: The first panel of the table presents results for models using our preferred control group.

Control: ⩾10, 1-9: The second panel of results expands the definition of our control group to include observations with a second BLL test less than 5.

Control: Only one test ⩾ 10: The third panel of results changes the definition of our control group to only include individuals with one BLL test and that test was ⩾10. This includes all of the individuals who tested once over the threshold but did not show up for a second confirmatory test.

Control: at least one test ⩾ 5: The fourth panel of results 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+: The fifth panel of results presents estimated effects from models that define the control group as those with initial BLL test results of 15µg/dL or more. Only those individuals with a test result of 15µg/dL or more are included in the control group.

Initial BLL FE: The sixth panel the table presents results 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.

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 based on 3rd through 8th grades and 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 A6: Falsification Test of Intervention using other BLL Thresholds

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
BLL=7		
False Intervention	−0.028	−0.042
	(0.092)	(0.083)
Observations	238	238
BLL=5		
False Intervention	−0.095	0.103*
	(0.067)	(0.059)
Observations	726	726
BLL=3		
False Intervention	−0.021	0.087
	(0.053)	(0.056)
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 A7: Effects of an elevated BLL intervention on summary index outcomes for siblings

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Younger Siblings		
Younger Sibling of Child (>10 , >10)	0.112	−0.455
	(0.263)	(0.306)
Observations	74	74
Older Siblings		
Older Sibling of Child (>10 , >10)	−0.184	0.139
	(0.784)	(0.567)
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 based on 3rd through 8th grades and 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 A8: Means by initial BLL test result

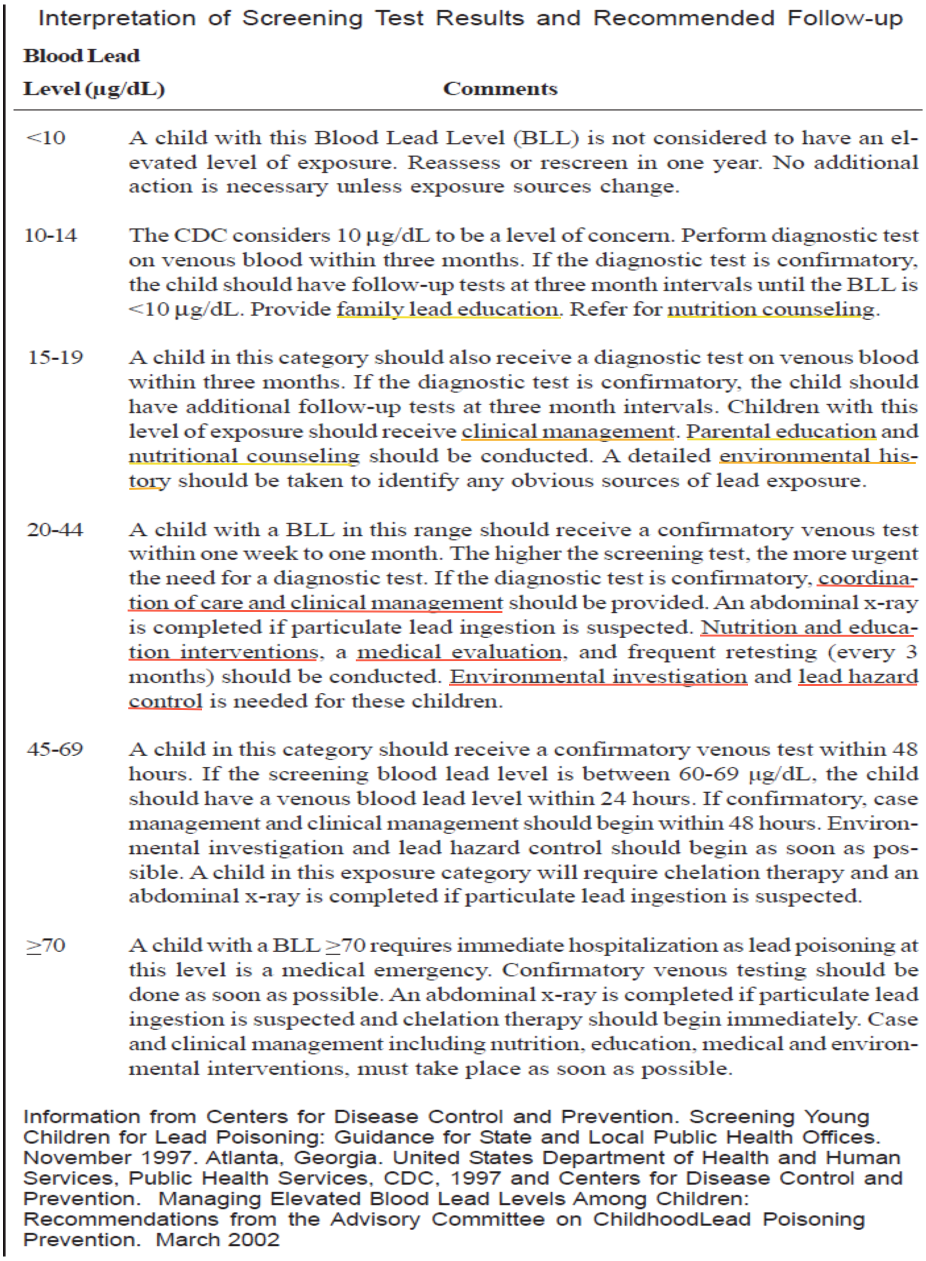
	BLL=1	BLL = 2	BLL = 3	BLL = 4	BLL = 5	BLL = 6	BLL = 7	BLL = 8	BLL = 9	BLL⩾10 cntrl B	BLL=10-20 interv.	BLL⩾20 interv.
Blood lead level (μg/dL)	1.000	2.000	3.000	4.000	5.000	6.000	7.000	8.000	9.000	11.843	15.473	27.296
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(3.995)	(5.685)	(9.227)
<u>Education Outcomes</u>												
Reading Test Score (avg 3-5th grade)	0.089	−0.017	−0.145	−0.268	−0.299	−0.380	−0.412	−0.461	−0.397	−0.484	−0.540	−0.149
	(0.973)	(0.944)	(0.950)	(0.937)	(0.933)	(0.932)	(0.911)	(0.953)	(0.948)	(0.930)	(0.862)	(0.680)
Math Test Score (avg 3-5th grade)	0.069	−0.011	−0.144	−0.272	−0.303	−0.401	−0.402	−0.459	−0.371	−0.425	−0.501	−0.346
	(0.977)	(0.951)	(0.952)	(0.935)	(0.923)	(0.925)	(0.907)	(0.930)	(0.909)	(0.930)	(0.827)	(0.760)
Reading Test Score (avg 6-8th grade)	0.141	0.015	−0.122	−0.225	−0.286	−0.328	−0.390	−0.405	−0.389	−0.423	−0.434	0.056
	(0.948)	(0.940)	(0.945)	(0.939)	(0.948)	(0.907)	(0.902)	(0.964)	(0.942)	(0.934)	(0.830)	(0.598)
Math Test Score (avg 6-8th grade)	0.110	0.010	−0.126	−0.233	−0.270	−0.342	−0.366	−0.396	−0.349	−0.392	−0.329	−0.238
	(0.965)	(0.954)	(0.946)	(0.916)	(0.900)	(0.874)	(0.867)	(0.886)	(0.916)	(0.898)	(0.843)	(0.740)
Repeat a grade (grades 3-9)	−0.096	−0.117	−0.152	−0.177	−0.207	−0.231	−0.251	−0.251	−0.262	−0.245	−0.211	−0.167
	(0.294)	(0.321)	(0.359)	(0.382)	(0.406)	(0.422)	(0.434)	(0.434)	(0.440)	(0.430)	(0.410)	(0.381)
<u>Behavorial Outcomes</u>												
Total Days Suspended from School (6th-10th grade)	2.619	3.699	4.954	5.831	6.903	7.780	8.970	8.450	7.933	10.578	6.961	7.519
	(10.793)	(13.035)	(15.627)	(16.227)	(18.789)	(19.383)	(20.611)	(21.444)	(18.798)	(24.711)	(14.488)	(13.871)
Total Days Absent (6th-10th grade)	13.405	16.114	18.657	20.627	23.462	25.907	29.706	25.320	25.810	29.894	23.047	24.778
	(25.251)	(29.017)	(32.830)	(33.032)	(39.222)	(41.563)	(46.933)	(40.708)	(41.220)	(45.996)	(36.081)	(24.292)
Total School Reported Crimes/Incidents (6th-10th grade)	0.738	0.981	1.191	1.372	1.553	1.671	1.921	1.776	1.523	2.010	1.566	1.222
	(2.785)	(3.530)	(3.746)	(3.851)	(4.233)	(4.313)	(4.821)	(4.386)	(3.923)	(4.925)	(3.257)	(2.082)
Ever Arrested	0.029	0.039	0.047	0.065	0.076	0.085	0.086	0.098	0.094	0.098	0.074	0.000
	(0.169)	(0.193)	(0.212)	(0.246)	(0.265)	(0.279)	(0.280)	(0.297)	(0.292)	(0.297)	(0.263)	(0.000)
Ever Arrested - Violent	0.013	0.015	0.023	0.026	0.032	0.038	0.037	0.046	0.041	0.052	0.025	0.000
	(0.113)	(0.121)	(0.148)	(0.158)	(0.176)	(0.191)	(0.189)	(0.210)	(0.198)	(0.222)	(0.156)	(0.000)
Ever Arrested - Property	0.011	0.018	0.020	0.027	0.034	0.043	0.035	0.043	0.039	0.047	0.041	0.000
	(0.107)	(0.132)	(0.140)	(0.163)	(0.181)	(0.203)	(0.185)	(0.202)	(0.194)	(0.212)	(0.200)	(0.000)
Observations	3,015	5,390	6,239	5,137	3,471	2,203	1,357	885	568	1,174	129	27

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 based on 3rd through 8th grades and 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.

Figure A1: 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).