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

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Abstract

Lead (Pb) pollution is a pervasive threat to childhood health and development since it is associated with substantial cognitive and behavioral impairments. This paper estimates the long-term effects of early-life public health interventions triggered by test results that show an elevated blood lead level (EBLL). We measure the long-term impact of the standard response recommended by the U.S. Centers for Disease Control (CDC) for lead-poisoned children using linked administrative data from Charlotte, North Carolina. Individuals with two consecutive tests over a specific blood lead level (BLL) threshold are assigned an intervention whereas individuals with an initial test over the threshold and a subsequent test just under the threshold are not. We compare later-life education and behavior outcomes between these two groups. The standard intervention for two elevated tests includes a combination of the following treatments: provision of information to parents on ways to reduce household exposure, environmental investigation, referral to lead remediation services, nutritional assessment, medical evaluation, and referral to public assistance programs. Using detailed administrative data on lead test results, schooling, and criminal history records, we find that intervention reduces adolescent antisocial behavior and increases academic achievement. The magnitudes of our estimates suggest that the education and behavioral deficits previously associated with early-life lead exposure can largely be reversed by intervention.

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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 in many countries, lead exposure is still widely recognized as a major public health issue. It is estimated that approximately one out of every four homes in the United States contains a significant lead paint hazard (Jacobs et al., 2002). 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 contributes to the intergenerational transmission of inequality through its impact on early-life health (Aizer and Currie, 2014).

A growing literature emphasizes the profound impact of early-life health on the development of cognitive and non-cognitive skills (Cunha and Heckman, 2008; Currie and Almond, 2011). Recent research suggests that early health and education interventions can yield large long-term benefits.[2] For example, the Carolina Abecedarian Project provided a package of treatments focused on social, emotional, and cognitive development to disadvantaged children from birth through age five. Long-term benefits from this extensive intervention include increases in educational attainment, declines in criminal activity, and improved adult cardiovascular health (Barnett and Masse, 2007; Anderson, 2008; Campbell et al., 2014). Other early interventions are also associated with substantial benefits, 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).

Given the large body of evidence connecting childhood lead exposure to cognitive and behavioral deficiencies[3], the U.S. Centers for Disease Control (CDC) recommends an intervention for children whose blood lead levels (BLLs) exceed an alert threshold. Blood lead tests and any resulting intervention are typically administered to children between the age of one and three. The elevated blood lead level (EBLL) intervention includes some combination of the following treatments: provision of information to parents on ways to reduce household exposure, environmental investigation, referral to lead remediation services, nutritional assessment, medical evaluation, and referral to public assistance programs.

Since the CDC lowered the alert threshold to 10 micrograms per deciliter (μg/dL) and published new recommendations in 1991, state and local health departments across the United States have provided an EBLL intervention to millions of children.[4] Despite the large-scale

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

[3]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: 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). See Appendix Section A for a summary of the effects of lead on cognitive and behavioral outcomes.

[4]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:

implementation of these programs, previous studies have not evaluated the impact of the intervention. Therefore, our study offers two primary contributions. First, we provide novel estimates of the long-term cognitive and behavioral impact of the standard public health response to EBLLs in the United States. Second, we contribute to the existing literature that measures benefits associated with various early-childhood health interventions. The EBLL intervention is unique to this literature because of its design and scale. Similar to the Abecedarian programs, the EBLL intervention collectively addresses many aspects of early-life health and economic disadvantage. Unlike programs applied to small groups of disadvantaged children, the EBLL intervention is widely applied as a public health response to an environmental toxin.

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. Our data covers the entire population of Charlotte, NC. Charlotte contains the eighteenth largest school district and is representative of other large urban areas in the United States. Similar to many other state and local health departments, EBLL intervention policy in Charlotte is based on CDC guidelines. An EBLL intervention is triggered by two consecutive blood lead tests over an alert threshold of 10 μg/dL. Individuals exceeding this threshold only once do not require an intervention. To identify the effects of intervention, we compare education and behavior outcomes for children testing twice over the threshold with those who only have one test over the alert threshold and a second test just under the threshold. Blood lead testing is the most common method to screen and diagnose lead exposure, but is a fairly inaccurate measure of past exposure due to a short half-life of lead in blood (30 days) and high contamination risk during commonly used testing procedures (ATSDR, 2007; Kemper et al., 2005; CDC, 1997). In fact, we observe a great deal of variation between a child's first and second BLL test result. While inaccuracy in testing makes it difficult to determine actual underlying levels of exposure, these detection challenges directly contribute to our identification strategy. Conditional on a first test with elevated BLL, assignment to intervention will differ between individuals with similar lead exposure simply due to idiosyncratic variation in recorded BLL due to current testing procedures. We find strong support for this identification assumption by demonstrating balance on observable characteristics (including those highly correlated with exposure risk such as neighborhood and age of housing) between our intervention and control groups.

We estimate a decrease in antisocial behavior and an increase in adolescent educational performance among individuals whose BLL test results require an intervention. Relative to our control group, we estimate a 0.182 standard deviation decrease in antisocial behavior and a 0.134 increase in educational performance among children who were eligible for an EBLL intervention several years prior.[5] While all interventions include the provision of important information about household exposure reduction to the parents of lead-poisoned children, a higher-intensity intervention is triggered by two tests over a threshold of 20μg/dL. This intervention involves medical evaluations, developmental assessments, mandatory home environment investigations, and nutrition interventions. We estimate a 0.387 standard deviation decrease in antisocial behavior and a 0.357 standard deviation increase in educational performance associated with

//www.cdc.gov/nceh/lead/data/national.htm [accessed Jan 24 2015]). Projecting testing rates and results back to 1991 imply millions of confirmed EBLL cases.

[5]For education and behavior 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). We do not include educational measures past tenth grade because we have very few cohorts reaching ages seventeen or eighteen by 2011 (the last year of our school outcome data).

the higher-intensity intervention. These estimates are large in magnitude. In fact, the negative effects of high levels of exposure on education and antisocial behavior are almost reversed by the intervention—children who test twice over the alert threshold exhibit similar levels of these outcomes as children with minimal levels of exposure (BLL<5μg/dL).

To better understand the importance of reducing the amount of lead in the household environment, we investigate whether intervention is associated with reductions in exposure based on follow-up BLL test results. We also merge data from LeadSafe Charlotte, an organization funded through the Lead-Based Paint Hazard Control Grant Program operated by The U.S. Department of Housing and Urban Development (HUD), to assess whether remediation is associated with long-term reductions in exposure at a particular address. Prior evaluations of household lead remediation programs through randomized controlled trials document significant decreases in household dust lead levels (Sandel et al., 2010) and the number of EBLL cases (Jones, 2012). However, randomized control trials evaluating lower-cost parental education and household dust-control 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).[6] Overall, our data suggests that intervention reduces residential exposure and we detect larger treatment effects among those who exhibit the largest declines in BLLs. However, we cannot separate benefits due to reduced exposure from selection among those families who respond more vigorously to EBLLs. It is possible that reductions in exposure is not the primary mechanism driving the estimated benefits.

If reductions in environmental exposure cannot fully explain our results, long-term benefits are expected through other mechanisms since the EBLL intervention includes elements common to other successful programs, including: home visits from health workers; increased medical care; referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC); and developmental assessments.[7] In our setting, the higher-intensity intervention involves some combination of these treatments and is associated with large long-term benefits. In contrast, benefits from lower-intensity EBLL interventions focused on parental education and nutritional counseling are smaller in magnitude and are not statistically significant. This pattern of results is consistent with the early-life intervention literature—the majority of interventions which yield long-term benefits involve significant medical, financial, and educational investments during early childhood.

We are not able to estimate the effects of specific elements of the EBLL intervention package separately, which is a limitation common to evaluations of other early-life interventions.[8] While further research is needed to investigate the mechanisms by which individuals benefit from EBLL interventions, cognitive and behavioral effects associated with the standard intervention

[6] 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] The intervention can result in increased early-life medical care after a medical evaluation and requires home investigation by local health workers; Benefits have been documented for programs which increase medical care at birth (such as those triggered by Very Low Birth Weight) or increase access to medical professionals (e.g. the Nurse-Family Partnership). The intervention includes a nutritional assessment and referral to the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC); in prior studies, improved early-life nutrition and access to public assistance programs is associated with large benefits (Hoynes et al., 2011, 2012). Finally, an EBLL intervention includes a developmental assessment and can result in a referral to child development services which may have long-term effects on social, emotional, and cognitive development; large benefits are found from high-quality early childcare and preschool programs which focus on these developmental processes (e.g. Abecedarian, Perry Preschool, and Head Start).

[8] 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.

package are still relevant in evaluating current public health policy. Public health organizations have recently stated that no BLL should be considered "safe" and 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 EBLLs in Charlotte. Section 3 outlines our empirical strategy and how we identify our intervention and control groups. Section 4 describes our data and characterizes our intervention and control groups with summary statistics. Section 5 discusses estimated effects of intervention on a variety of educational and behavioral outcomes and Section 6 investigates the mechanisms driving our main results. Section 7 provides some concluding remarks. An Appendix includes a description of the evidence linking lead exposure to cognitive and behavioral outcomes, a description of our data and linking process, and supplemental results.

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

The U.S. Centers 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 health-care providers about childhood lead poising; and to implement prevention measures to reduce children's 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 indicated a blood lead level greater than 10μg/dL, a confirmation test was required within 6 months. If a second consecutive test indicated a blood lead level greater than 10μg/dL, a set of interventions is implemented based on the level of lead detected. 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

[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).

[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 that 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.

to 1991.[13]

The set of interventions for our entire sample of children with two consecutive tests over 10μg/dL include the following: provision of nutritional/environmental information; a referral to WIC for families not already participating; an environmental history interview to identify sources of lead; a referral to the LeadSafe Charlotte program for cases identified as high lead risk in the home; and, testing of other children under age 6 in household. 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$20μg/dL, we do not report heterogeneous effects for individuals testing with two tests of 15$\leqslant$BLL$<$20 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.

The formal protocol for the standard intervention includes first taking a medical history regarding any symptoms, developmental history as well as previous blood lead level measurements and family history of lead poisoning. The health care provider then performs an environmental history interview where family members are asked about the age, condition, and on-going 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 health care 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.[14]

The family is referred to the LeadSafe Charlotte remediation program whenever there is any indication of lead in or around a residence. LeadSafe Charlotte is a program funded through the Lead-Based Paint Hazard Control Grant Program operated by The U.S. Department of Housing and Urban Development (HUD). Since 1998, LeadSafe Charlotte has received over $17 million dollars from HUD to reduce lead-based paint hazards in over 2,000 homes within Charlotte-Mecklenburg County.[15] Owners of a property built before 1978 who meet certain income eligibility requirements and have children under 6 are eligible for inspection and remediation services through the program.[16] Eligible property owners may apply to the Leadsafe program if they suspect that lead is present inside or outside the home. Approximately 70% of applicants are found to have lead-based paint hazards remediation typically includes removing and replacing windows and doors; painting or siding the exterior of homes; and repairing doors to avoid chipping within the door frame when opening and closing. The average cost of these repairs in our dataset of LeadSafe homes was $6,832 and represent a

[13] 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 our time period of analysis (1990-2005), the 5μg/dL threshold does trigger any policy recommendations.

[14] 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.

[15] Information about the LeadSafe Charlotte program was obtained through a informational web page maintained by the Charlotte-Mecklenburg county government: http://charmeck.org/city/charlotte/nbs/housing/pages/leadbasedpaint.aspx [accessed December 13, 2014].

[16] The income eligibility requirement states that the property owner must have a household income no greater than 80% of the median income for the household size.

nontrivial improvement in the quality of housing.

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 increased 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 that contain lead as well as water sources for the family. The health care provider also 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. A standardized developmental screening test is recommended with referrals to the appropriate agency for further assessment in cases of developmental delays.

3. Empirical Framework

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

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

where Y_i is an outcome for individual i and $\mathbf{X}_i$ includes a wide range of controls.[17] Each outcome is regressed on an indicator, $Intervention_i$ for whether child i received two consecutive tests over the intervention threshold of 10μg/dL. Since the presence of lead paint is heavily concentrated in older, residential neighborhoods, standard errors are clustered at the Census Block Group (CBG) level.

We also allow for heterogeneous effects based on the intensity of intervention by splitting $Intervention_i$ and estimating the following model:

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

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

Our primary results focus on intervention effects on 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.[18] Besides dealing with concerns about multiple hypothesis

[17] We include indicators for gender, race/ethnicity, birth year, age at blood test, low birth weight status, parental education level, single family home, built pre 1978, as well as controls for the average previous lead test results associated with the residential address listed and 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.

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

testing, a summary index can be potentially more powerful than individual-level tests due to random error in outcome measures. Each summary index is a weighted mean of standardized outcomes. The antisocial behavior index includes 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 educational performance index includes 3rd through 8th grade math and reading test score results, as well as grade retention between 1st and 9th grade.[19] We also estimate and present results separately for individual outcomes 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 to control for any parental response to what public health officials consider a 'BLL of concern'. Our control group includes individuals whose first blood lead test exceeds the alert threshold of 10µg/dL, but the second test results in a BLL between 5 and 9µg/dL. We also provide results using alternative control groups in robustness checks presented in the Appendix.

Causal effects associated with public health interventions can be difficult to identify with these types of interventions since individuals are not randomly assigned to intervention. Several important identification concerns arise, such as: Are there differences in the attributes of our intervention and control groups? How do intervention and control groups differ in actual levels of lead exposure? and, Is the behavior of families in the control group affected by an initial test above an alert threshold?

First, in order to identify a causal effect of the intervention, we must assume that unobservable determinants of our outcomes (ϵ_i) are not correlated with whether an individual tests twice over the 10µg/dL threshold. To assess whether intervention is plausibly exogenous to individual characteristics, we compare observable characteristics (including measures of parental quality, health-at-birth, housing quality, and neighborhood quality) across the intervention and control groups and conduct a formal balance test in Section 4. In our setting, assignment to intervention for those near the threshold is plausibly exogenous due to the fact that blood lead testing provides a noisy measure of abrupt changes to lead intake for relatively short exposure periods (ATSDR, 2007). For individuals with high exposure, BLLs may not represent an accurate measure of lead exposure since most lead is stored in the bone (ATSDR, 2007). Moreover, there is a high risk of contamination during testing procedures utilizing capillary sampling (the "finger-stick method") which is the method most commonly used for initial tests (ATSDR, 2007; Kemper et al., 2005; CDC, 1997). Variation in test results caused by these factors can cause assignment to intervention or control which is unrelated to observed or unobserved characteristics.

We observe a great deal of variation in test results between a child's first and second test. Figure 2 plots the relationship between the first and second BLL test result and displays the distribution of our treatment and control samples by combinations of first and second test results. A substantial fraction of individuals with an initial BLL test over the threshold of 10 µg/dL receive a subsequent test result below the threshold.

While testing is inaccurate and can assist with identification near the threshold, as we move further away from the threshold, individuals in the intervention group likely have higher levels of exposure risk than our control group. Our estimated intervention effects may be biased to

of the steps in the Appendix.

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

the extent that they differ along exposure and other unobserved attributes. However, based on patterns within our data as well as prior results previously discussed, benefits associated with intervention would be biased downwards by negative effects of higher lead exposure among the treated group on educational and behavioral outcomes. A downward bias implies that our results represent conservative estimates of the long-term benefits associated with the interventions evaluated. To address this potential bias, we check that our results are robust to models including flexible controls for BLL test results including BLL fixed effects and limiting the control group to individuals with higher initial BLLs.

Finally, although an intervention is only triggered after a follow-up test confirms an EBLL, there could be changes in behavior among parents of children in the control group after an initial test indicates a level of exposure considered to be dangerous. To investigate whether any "threshold effects" are present, we observe whether there are any discontinuities in our outcomes at the 10μg/dL threshold among tested children who do not trigger an intervention. We also investigate whether results are consistent using alternative control groups such as those with an initial test just below the alert threshold. We do not find evidence of any threshold effects. Moreover, to the extent there are changes in behavior among the control group, our estimated intervention effects would, again, most likely be biased downwards since we expect a threshold response to benefit individuals in the control groups.

Throughout our analysis we refer to our estimates as intervention (or treatment) effects. However, our estimated effects represent a combination of several effects. First, since we do not directly observe participation in any intervention programs, α represents an "intention-to-treat" (or "ITT") treatment effect which is a combination of the direct impact of intervention on outcomes and the probability of compliance with the intervention.[20] Second, the estimated impact includes the role of parental or other inputs that react to a confirmed EBLL. For example, intervention could directly impact child nutrition and the level of lead in the home environment but also have an indirect impact on the amount of care and attention provided by a parent. While the various components of this total effect would be extremely useful in designing early childhood intervention programs, our estimate, $\hat{\alpha}$, is the most relevant for evaluation of the CDC-recommended public health response to EBLLs since 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.

4. 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 through 1997 in Charlotte-Mecklenberg County, North Carolina.[21] Blood lead surveillance data is maintained by the NC Childhood Lead Poisoning Prevention Program of the Children's Environmental Health Branch.[22] This dataset includes BLL test results, which allow us to determine which

[20] 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 the implementation.

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

[22] 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.

children received various lead policy interventions due to two tests with BLL of 10 μg/dL or above.[23] While the majority of tested individuals have low BLL levels, a sufficient number of tests indicate BLLs right around our threshold of interest for policy interventions at 10 μg/dL (see Figure 1 for a distribution of initial BLL test results).[24]

We match individual children who receive blood lead tests to two additional databases in order to examine the impact of EBLL 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.[25] 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.[26]

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.[27] 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.

In order to control for parental and housing factors which may influence outcomes, we draw on two additional databases. The first database is the universe of birth certificate records from the state of North Carolina from 1990-1997 from which we obtain birth weight and parental years of education.[28] The second database is county assessor's data for all parcels on an annual basis from 2002-2012 with property sales back to 1994. 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 from 1995-2012. This database allows us to incorporate information on housing stock and neighborhoods and directly account 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.[29]

Tables 1A and 1B provide summary statistics for our intervention group and control group separately after merging all datasets and limiting our analysis to individuals born prior to 1998.[30] Individual attributes are similar between these groups indicating balance on observables,

[23]This data also includes child's name, gender, birth date, test date, blood lead level (BLL) and home address.

[24]The full dataset includes BLL results for 53,704 individuals born between 1990 and 2002.

[25]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>10.

[26]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.

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

[28]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.

[29]The lead database is matched to parcels records 86% of the time with differences primarily a result of incomplete homes address information.

[30]Tables 1A and 1B provide summary statistics for the entire population after merging all datasets and limiting our analysis to individuals born prior to 1998. Not surprisingly, we observe worse educational and behavioral outcomes for children who receive a blood lead test compared to untested children. Lead tested individuals are also more likely to live in an older home, have less educated parents and live in lower income neighborhoods. Focusing on different BLL groups in columns 3 and 4, we see that higher levels of lead exposure are associated with worse education and behavioral outcomes.

yet the intervention group has substantially better education and behavioral outcomes. Figure 3 displays mean outcomes for each integer level of initial BLL result as well as mean outcomes for the control group and intervention groups (split at 20μg/dL). Intervention effects are also evident from many of the panels of Figure 3: average outcomes become worse as BLLs increase (most often monotonically) until a sharp change for the intervention groups. This change is most evident for the antisocial behavioral outcomes and consistent with estimated intervention effects.

We formally test if our policy intervention and control groups are balanced on observables in Table 2. We estimate the effect of a wide range of individual, housing, and neighborhood observable characteristics on the probability of receiving two BLL tests above the intervention threshold. Table 2 reports estimates of the relationship between observable characteristics and intervention for the total intervention group as well as the group split by the intensity of the intervention. The first column compares the standard intervention group (BLL⩾10μg/dL) to our control group; the second column compares the lower level intervention group (10μg/dL⩽ BLL⩽19μg/dL) with the control group; and the third column compares the higher level intervention group (BLL⩾20μg/dL) with the control group. Across all specifications, we cannot reject a null hypothesis that all covariates are equal to zero, providing confirmation that our intervention and control groups are reasonably balanced.

Given that our ability to match lead data ranges from 54% to 86%, we are concerned that matches may be related to to demographics or parental factors. Names from certain ethnic groups may have lower match rates due to clerical errors and parents that fail to properly fill out forms for school 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 A2 that determines if non-matched individuals are more likely to be assigned to the intervention group. In these results, we include all lead tested individuals in our intervention and control groups. Coefficients on indicators 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. Results of a F-test that all missing database variable indicators are jointly equal to zero 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.

5. Results

After a second test confirms an EBLL, the NC Department of Health requires the implementation of the interventions recommended by the CDC (as listed in Figure A1). Intervention always includes further BLL tests. To assess whether individuals comply with intervention after an EBLL is confirmed we estimate the effect of intervention on the total number of tests recorded in the blood lead surveillance data. Column (7) of Table 5 shows that compared to the control groups, those with confirmed EBLLs have 3 more tests indicating that, on average, our treatment group is complying with at least this aspect of the intervention. While this result provides 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 on intervention program participation.

Academic performance reflects the development of cognitive functioning as well as the development of non-cognitive skills. The first panel of Table 3 estimates Eq. (1) for our education summary indexes and for individual outcomes grouped by different grade levels. Combining math and reading test scores between 3rd and 8th grade and grade retention outcomes between 1st and 9th grade into a summary index, we estimate a statistically significant 0.134 standard deviation increase in educational performance associated with the EBLL intervention. While effects for early education outcomes (3rd through 5th grade) are imprecise, they are consistent with benefits from intervention. The largest effects appear to emerge in later education outcomes. For example, we estimate close to a 0.2 standard deviation increase in reading test scores during 6th through 8th grade for the intervention group.

Early-life lead exposure has previously been linked with increases in behavioral problems, conduct disorders, and adult criminal activity (EPA, 2013). 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 3 reports a large and significant decline in antisocial behavior associated with EBLL intervention. Relative to the control group, we estimate a 0.182 standard deviation decrease in our antisocial behavior summary index associated with intervention. This represents a very large decline from the average index value of 0.15 for the control group. The pattern of estimates across individual outcomes of suspensions, absences, school crimes, and criminal arrests reported in Table 3 consistently demonstrate improvements associated with intervention.

We estimate much larger effects for the higher-intensity interventions. Effects of the high-intensity intervention are not statistically significant for all education 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 4 reports a 0.357 standard deviation increase in our educational performance index. We estimate a 0.387 standard deviation decrease in our antisocial behavior index associated with the set of interventions triggered by BLL test results $\geqslant 20\mu g/dL$ which is statistically significant at a 1% significance level.

Overall, these results suggest large long term educational and behavioral benefits form more intensive intervention. Estimated effects of the high intensity intervention on education and behavior indexes are similar in magnitude to those found from the Abecedarian and Perry Preschool programs. Anderson (2008) reports around a 0.4 standard deviation effect on a summary index from the Abecedarian intervention and similar sized effects for his re-evaluation of the Perry Preschool results. However, we interpret these estimates with caution since they are based on a small number of individuals eligible for the high-intensity treatment in our sample.

We conduct several robustness checks to address identification concerns previously discussed in Section 3. First, we present results form a regression discontinuity model using the lowest BLL test result as the running variable and limiting our sample to those with a running variable between 7 and $12\mu g/dL$. These results are presented in Table A3. While estimated effects are associated with large standard errors, the direction and magnitude of results are mostly consistent with those from our preferred specifications. Discontinuities in outcomes at both intervention thresholds are evident in Figure A2.

Second, to examine whether our results may be affected by a bias arising from different levels in underlying exposure between our intervention and control groups, we estimate results flexibly controlling for a measure of exposure through the inclusion of BLL tests results as linear controls as well as through including indicator variables for initial and average BLL test results. Through including indicators for BLL categories, our intervention effects are identified from variation in outcomes between intervention and control individuals with identical initial

BLL test results or identical average levels of exposure based on the first two test results. These results are presented in Table A3. The magnitude of our estimates are similar to those in our main specifications but less precise. This is not surprising given we less variation in intervention within fixed values of BLL results.

Results from models including indicator variables for initial BLL test results (presented in the fourth panel of Table A3) 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. This model identifies treatment effects by comparing outcomes for individuals with identical initial BLL test results (who we assume receive the same information about their child's level of exposure). To test whether there are changes in behavior among the control group induced by an initial test over the alert threshold of 10μg/dL, Panel A of Figure 4 plots estimated index outcome measures for individuals (who do not become part of the intervention group) at each integer BLL. No threshold effects (change in outcomes) at 10μg/dL are detected for any of the summary index measures. We also do not observe any discontinuities at other potentially salient thresholds such as 5μg/dL.[31]

We also test whether our results are specific to the control group chosen, we estimate Eq. (1) using six alternative definitions of the control group. Again, these results are presented in Table A4 and are consistent in magnitude with those found in our main specifications. All of these results suggest that our estimated intervention effects are not substantially biased by an underlying effect of higher lead exposure.

Finally, we match intervention and control individuals to siblings in our data to test whether EBLL intervention impacts other children in the household. Table A6 displays estimates from Eq. (1) for the small number of siblings we were able to match to the intervention and control households given our restrictions described in detail in the Appendix. 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 very few observations and are associated with very large standard errors.

6. Mechanisms

The substantial improvements associated with the EBLL 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. Three primary channels emerge by which the early childhood environment is improved after an EBLL intervention: a reduction in the prevalence of lead in the household which limits damage to neurodevelopmental processes; improvements in care and nutrition through the provision of important information to the parents of lead-poisoned children; and, an increase in the early-life presence of public agencies through activities such as monitoring and assessment of early life health and development as well as through the provision of public assistance.

To investigate whether benefits are due to reductions in levels of exposure, we first assess whether intervention reduces exposure by plotting the change in BLLs following a second test

[31] We formally show no effects from the 5μg/dL threshold in Table A5 by recreating our main results using two tests between 5 and 9 μg/dL as our intervention group and individuals with one test 5-9 μg/dL and a second test 2-4 μg/dL as our control group.

result over 10μg/dL. For those individuals who continue to receive BLL tests, we observe BLLs drop gradually to levels below the 10μg/dL alert threshold as depicted in Panel B of Figure 4. However, we do not find evidence that the final BLLs among our intervention group are lower than the final BLLs among the control group in a specification similar to Eq. (1) which replaces the dependent variable with one measuring the final BLL test result for our intervention and control groups. The final BLL values in our intervention group are 3μg/dL higher on average than those for the control group (Column (6) of Table 5).

The most immediate and expensive way to reduce environmental exposure within residences identified to contain a lead-based hazard is through a remediation service. If an inquiry or home investigation identifies a potential residence-based hazard for children exceeding the alert threshold, families are referred to the LeadSafe Charlotte organization which provides remediation services to eligible families. Table 5 report a increase in the probability of a LeadSafe application and remediation service (Columns (4) and (5)) associated with an EBLL. Moreover, matching initial BLL tests at specific addresses to the LeadSafe application and remediation data, we do observe a decline in BLLs for the treated properties (see Panel C of Figure 4). We compare application properties with remediation properties to control for any selection bias caused by the types of families who choose participate in the LeadSafe program.[32] However, lead values after remediation include both prior residents as well as individuals that move into a property. Since the composition of new residents may be influenced by lead remediation, this small decrease in lead exposure is a combination of lead removal as well as changes in parental attributes that may influence lead exposure outside the home or from other sources.

To the extent reductions in exposure cause increases in education performance and decreases in antisocial behavior, we expect larger intervention effects among those with the lowest final BLLs. We estimate a model allowing the effect of intervention to differ for those whose final BLLs decline below the threshold 10μg/dL and for those whose BLLs do not decline below the threshold and present these estimates in Panels D and E in Figure 4. While the patterns are suggestive of larger intervention effects for those with lower final BLLs, effects based on the final BLL level are not statistically different from one another. Moreover, these heterogeneous effects could be driven by other elements of EBLL interventions in conjunction with reducing lead.

Overall, our results suggest that intervention may reduce levels of exposure but that the long-term benefits of these reductions may be limited. These results are consistent with exposure having a significant (and non-reversible) impact on important neurodevelopmental processes prior to intervention and/or with past exposure continuing to impact neurodevelopment since the half-life of the toxin in the brain has been estimated to be approximately two years (Lidsky and Schneider, 2003).

Table 5 estimates the effect of intervention on a variety of other potential responses observed in the data. We estimate a 7 to 8 percentage point decrease in the probability of relocating between BLL testing and CMS school enrollment which may be due to improvements in housing quality associated with any exposure reduction. Effects of intervention on property renovations and property sales are mostly insignificant but suggest that higher-intensity interventions may lead to more sales and less renovations. Property owners are required to disclose any prior EBLL test results among residents within contracts for either rental or sale. The patterns observed in these outcomes (move, renovated, property sold) could each be consistent with an improvement in housing quality triggered by the an application to the

[32] Approximately 30% of properties which apply to the LeadSafe Charlotte program do not receive remediation after a home inspection revealed no substantial risk.

LeadSafe Charlotte program.

To the extent information about dangerous levels of exposure causes changes in the household environment, we may also expect to see responses among those who only test once over the alert threshold of 10μg/dL. Despite the fact that official informational intervention programs are only triggered by a second confirmatory test during our time period of analysis, health workers may provide information on the dangers of exposure after the initial EBLL test result. We plot our summary index outcomes for all individuals without a second test triggering an intervention in Panel A of Figure 4 and do not observe any "threshold" effects at any particularly salient thresholds.

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 to elements more focused on the provision of information to parents. Table 4 reports estimated effects for this type of intervention more than twice as large as an informational intervention. Households containing a child with two tests over 20μg/dL appear slightly more likely to participate in the LeadSafe Charlotte program. 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") but we are not able to measure these responses.

According to health workers in Charlotte, NC, the higher-intensity intervention is also associated with a medical examination with particular attention to psycho-social and language development. Any deficiencies identified in this examination trigger referrals to appropriate public agencies. Overall, this level of intervention is associated with increased involvement of public agencies and participation in public assistance programs. 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 increasing participation and involvement of public agencies yield large benefits and are consistent with prior evaluations of early life programs.

7. Conclusion

In this first evaluation of the standard public health response to high levels of environmental exposure to lead, we find evidence that interventions can affect long-term educational and behavioral outcomes. We estimate large 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 and suggest that these interventions can mitigate and compensate for the deleterious effects of lead.

A massive amount of evidence across multiple disciplines consistently points towards substantial negative effects from 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.[33] However, very little evidence exists as to what types of programs and policies are effective in addressing these effects. While randomized

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

controlled trials have been used to evaluate other large-scale early childhood interventions (e.g. Head Start), RCT evaluations of public health responses to EBLLs may be difficult to implement due to ethical concerns. In fact, an RCT 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, evaluations of interventions related to lead exposure can be conducted using administrative data and 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 developing countries due to the prohibition of leaded gasoline, lead exposure still represents a major public health issue. In the United States, childhood exposure to lead over the last several decades is 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). Levels of lead exposure are lower in Charlotte than the national average due to a more modern housing stock.[34] Recognizing the current threat to childhood 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).[35]

Until communities make these long-run investments in reducing environmental levels of exposure, our results suggest that intervening early is critical to limit the damage from exposure. Our results can be used to inform policymakers considering intervention at lower levels of exposure detected. 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).[36] It is likely that increasing the frequency and intensity of intervention for lead-exposed children will yield a very large return considering the potential long-term effects on health and human capital.

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[34]According to CDC Blood Lead Surveillance statistics, 1.3 percent of children tested in Mecklenburg county had EBLLs in 1997 compared to over 7 percent nationally (source: http://www.cdc.gov/nceh/lead/data [accessed 28 February 2015]). More than 90 percent of the housing stock in Charlotte was built after 1950 when lead paint began to be phased out.

[35]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.

[36]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 exposure Budtz-Jørgensen et al. (2013).

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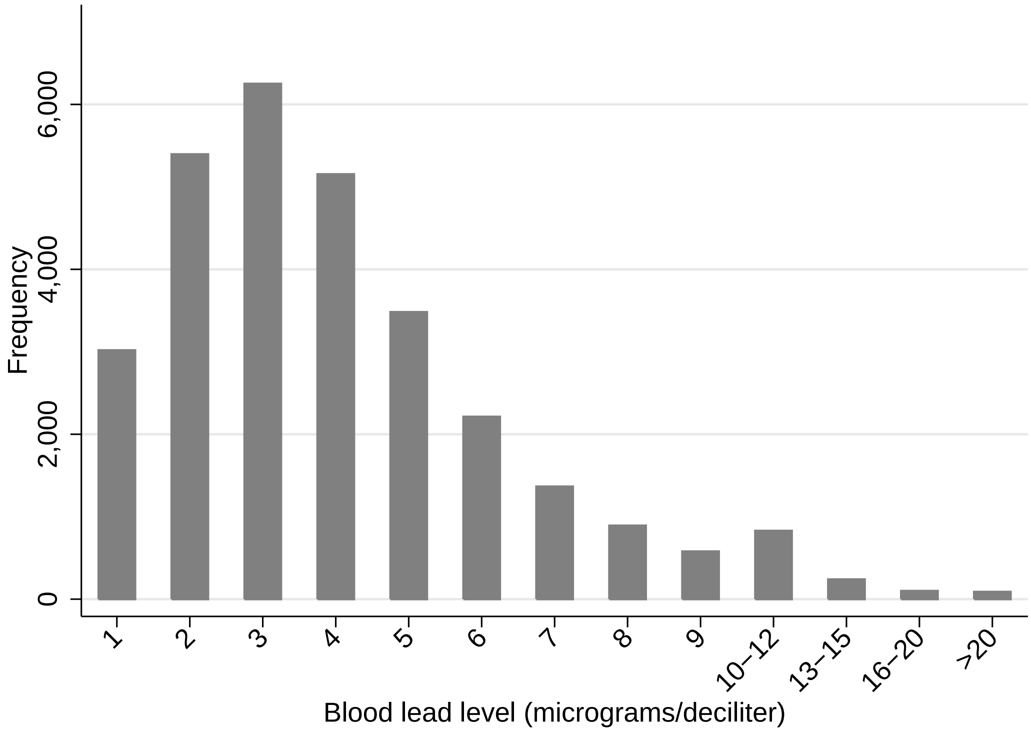
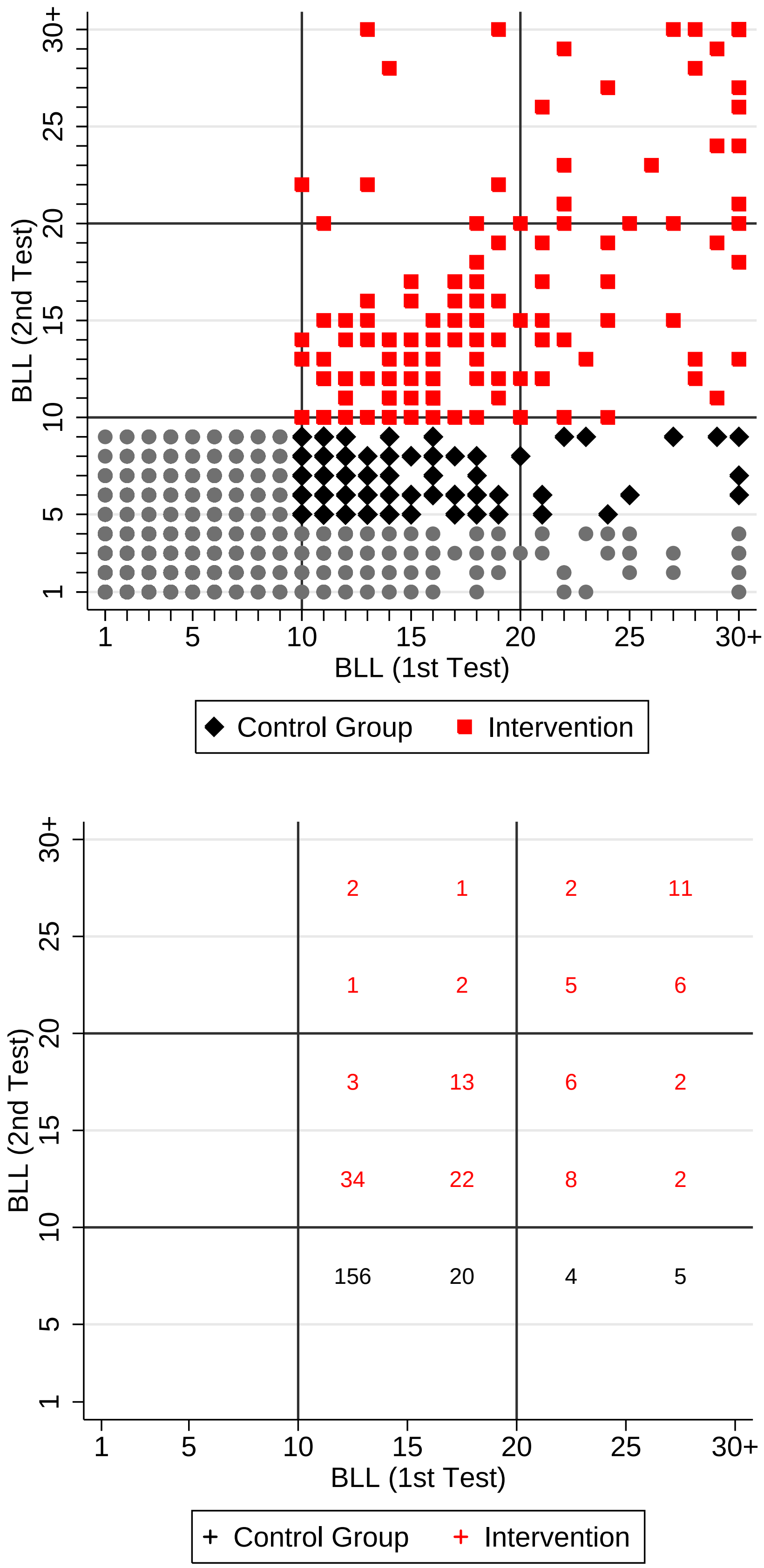
8. Figures and Tables

Figure 1: Distribution of initial blood level tests for all individuals with BLL data.



This histogram represents the distribution of initial BLL test results for all children in Mecklenburg County, NC born between 1990 and 1997. All data on blood lead levels is taken from the blood lead surveillance program under the NC Childhood Lead Poisoning Prevention Program within the NC Department of Health.

Figure 2: Blood Lead Testing Variation



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. Figure A plots the number of observations in our estimation sample for various combinations of first and second BLL test results.

Figure 3: Average Outcomes by Blood Lead Level

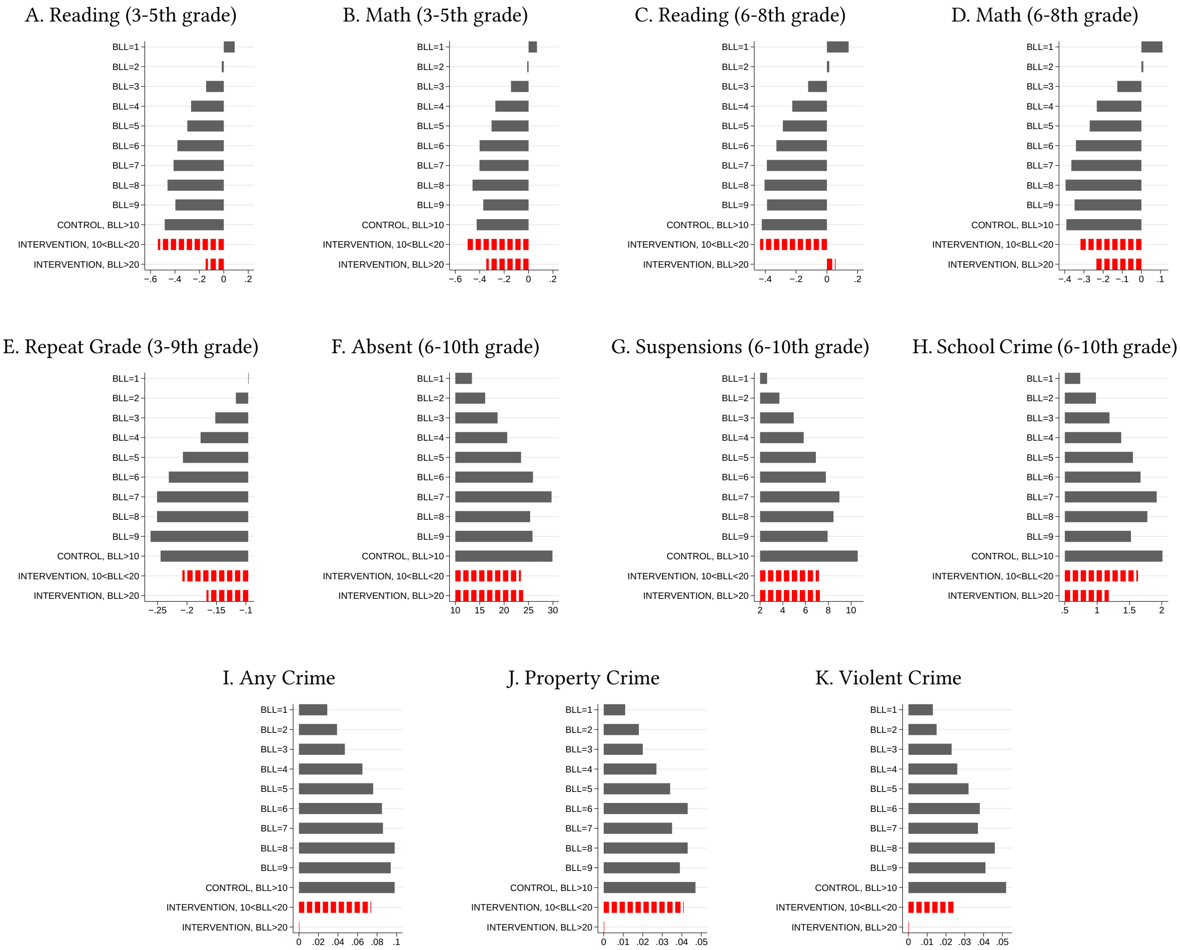
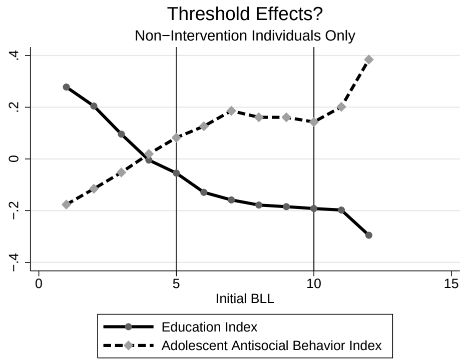


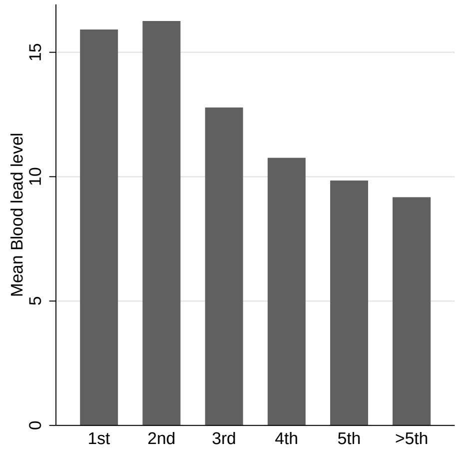
Figure Note: This figure depicts mean outcomes by the level of initial BLL test result. End-of-Grade Test scores based on 3rd through 8th grades and given mean zero and standard deviation of one based on NC state average test scores. Average Test Scores incorporate all test scores from grades 3rd-5th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

Figure 4: Mechanisms

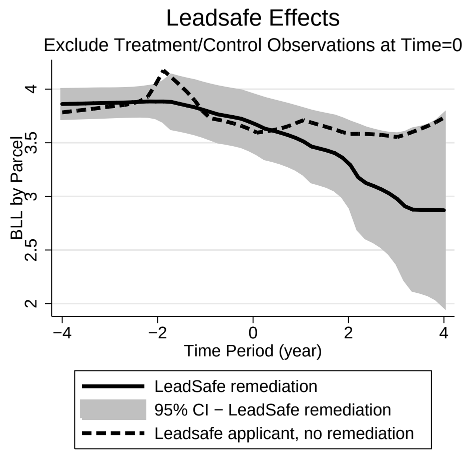
A. Any information threshold effects for those who do not trigger an intervention?



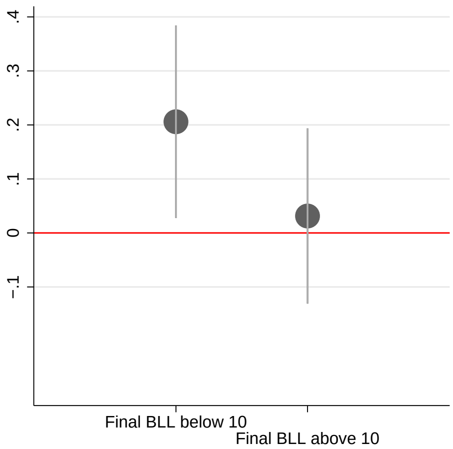
B. Reductions in BLL by order of test



C. BLL by parcel for LeadSafe Charlotte applicants



D. Effects on Education Index by Final BLL



E. Effect on Adolescent Antisocial Behavior Index by Final BLL

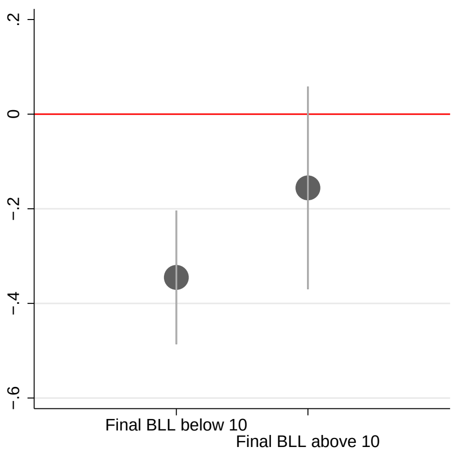


Figure Note: Figure A plots the relationship between BLL and outcome summary indexes for individuals that did not receive two tests with BLL >10. This figure allows us to inspect whether there are any information threshold effects after the initial BLL test. Figure B plots the mean blood lead levels for the Intervention group by the order of the test. Figure C plots the average BLL test results for properties which apply to the LeadSafe Charlotte program for those which get treated and those which apply but do not receive remediation after a home inspection revealed no substantial risk. Figures D and E display the estimated intervention coefficient for individuals grouped by the final blood lead test value recorded. Each bar measures an estimated coefficient relative to the control group.

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

	Intervention	Control
Blood lead level (μg/dL)	17.81	11.89
	(8.22)	(4.53)
Education Outcomes		
Education Index	0.08	−0.08
	(0.61)	(0.70)
Reading Test Score (avg 3-5th grade)	−0.44	−0.57
	(0.83)	(0.89)
Math Test Score (avg 3-5th grade)	−0.47	−0.51
	(0.82)	(0.91)
Repeat a grade (grades 1-5)	0.15	0.14
	(0.36)	(0.35)
Reading Test Score (avg 6-8th grade)	−0.32	−0.51
	(0.81)	(0.93)
Math Test Score (avg 6-8th grade)	−0.31	−0.45
	(0.82)	(0.86)
Repeat a grade (grades 6-9)	0.14	0.22
	(0.35)	(0.41)
Adolescent Antisocial Behavorial Outcomes		
Adolescent Antisocial Behavior Index	−0.16	0.15
	(0.47)	(0.96)
Total Days Suspended from School (6th-10th grade)	9.46	18.21
	(15.90)	(32.52)
Total Days Absent (6th-10th grade)	30.96	47.83
	(36.37)	(55.25)
Total School Reported Crimes/Incidents (6th-10th grade)	2.04	3.55
	(3.46)	(6.78)
Ever Arrested	0.07	0.18
	(0.26)	(0.38)
Ever Arrested - Violent	0.03	0.11
	(0.16)	(0.31)
Ever Arrested - Property	0.04	0.08
	(0.20)	(0.27)
Observations	120	185

Means and standard deviations are reported above. 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 1B: Means of demographic, housing, and neighborhood characteristics for intervention and control groups

	Intervention	Control
Background Characteristics		
Male	0.61	0.57
	(0.49)	(0.50)
Minority	0.78	0.78
	(0.42)	(0.41)
Stand Alone Residence	0.58	0.60
	(0.50)	(0.49)
Year Home Built	1958.70	1961.99
	(23.56)	(22.28)
Home Built pre 1978	0.79	0.78
	(0.41)	(0.41)
Past Lead Tests at a Home (mean µg/dL)	1.83	2.11
	(2.29)	(2.47)
Age at Blood Lead Test	1.82	1.71
	(1.33)	(1.10)
Birth Weight (ozs)	114.97	109.61
	(20.26)	(21.82)
Father Education (years)	12.31	12.54
	(2.63)	(2.26)
Mother Education (years)	11.92	11.55
	(2.94)	(2.19)
CBG Population Density (000s/sq mile)	3.28	3.23
	(2.07)	(2.20)
CBG Median HH Income	38.86	36.37
	(22.17)	(17.14)
CBG Percent in Poverty	0.47	0.55
	(0.41)	(0.47)
Observations	120	185

Means and standard deviations are reported above. 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.

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: Balancing test: Do observables predict an intervention?

	(1) Intervention (10+)	(2) Intervention (10-19)	(3) Intervention (20+)
Male	0.028	0.056	−0.066
	(0.059)	(0.058)	(0.049)
Minority	0.058	0.003	0.125*
	(0.077)	(0.076)	(0.065)
Home Built pre 1978	0.108	0.136*	0.011
	(0.068)	(0.069)	(0.065)
Past Lead Tests at a Home (mean µg/dL)	−0.017	−0.017	−0.014
	(0.031)	(0.032)	(0.024)
Stand Alone Residence	−0.067	−0.036	−0.071
	(0.072)	(0.078)	(0.071)
Birth Weight (ozs)	0.000	−0.001	0.002
	(0.001)	(0.001)	(0.001)
Father Education (years)	−0.001	−0.012	0.022
	(0.023)	(0.021)	(0.025)
Mother Education (years)	−0.006	−0.000	−0.012
	(0.013)	(0.014)	(0.012)
CBG Percent in Poverty	−0.111	−0.071	−0.073
	(0.075)	(0.072)	(0.066)
CBG Population Density (000s/sq mile)	0.000	−0.011	0.014
	(0.016)	(0.013)	(0.013)
CBG Median HH Income	0.001	0.001	−0.001
	(0.002)	(0.002)	(0.002)
F-Stat (p-value)	0.698	0.386	0.461
Observations	305	281	209

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

Dependent variable: Indicator equal to one if individual received two tests ⩾10µg/dL in column 1; an indicator based on two tests ⩾10µg/dL, but at least one test between 10-19µg/dL in column 2; and an indicator based on 2 tests ⩾20µg/dL in column 3. For column 2, we drop all observations with 2 tests ⩾20µg/dL. For column 3, we drop all observations with two tests ⩾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 3: Effects of an elevated BLL intervention on education and behaviorial outcomes

	(1) Education Index	(2) Reading (avg 3-5th)	(3) Math (avg 3-5th)	(4) Repeat Grade (1-5th)	(5) Reading (avg 6-8th)	(6) Math (avg 6-8th)	(7) Repeat Grade (6-9th)
Intervention	0.134**	0.168	0.090	0.029	0.199**	0.153*	−0.052
	(0.065)	(0.123)	(0.105)	(0.039)	(0.098)	(0.087)	(0.043)
Observations	305	245	250	305	241	242	305

	(1) Adolescent Antisocial Behavior Index	(2) Days Suspended (total 6-10th)	(3) Days Absent (total 6-10th)	(4) School Crimes (total 6-10th)	(5) Ever Arrested	(6) Ever Arrested Violent	(7) Ever Arrested Property
Intervention	−0.182**	−5.497**	−9.534**	−1.124*	−0.079*	−0.062*	−0.022
	(0.083)	(2.552)	(4.050)	(0.659)	(0.044)	(0.032)	(0.036)
Observations	305	305	305	305	305	305	305

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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 4: Effects of an elevated BLL intervention on education and behaviorial outcomes by intensity of intervention

	(1) Education Index	(2) Reading (avg 3-5th)	(3) Math (avg 3-5th)	(4) Repeat Grade (1-5th)	(5) Reading (avg 6-8th)	(6) Math (avg 6-8th)	(7) Repeat Grade (6-9th)
Intervention (20+)	0.357**	0.459**	0.212	0.036	0.580***	0.256	−0.067
	(0.142)	(0.178)	(0.173)	(0.078)	(0.181)	(0.171)	(0.082)
Intervention (10-19)	0.074	0.064	0.048	0.027	0.078	0.121	−0.048
	(0.072)	(0.130)	(0.115)	(0.043)	(0.101)	(0.095)	(0.048)
Observations	305	245	250	305	241	242	305

	(1) Adolescent Antisocial Behavior Index	(2) Days Suspended (total 6-10th)	(3) Days Absent (total 6-10th)	(4) School Crimes (total 6-10th)	(5) Ever Arrested	(6) Ever Arrested Violent	(7) Ever Arrested Property
Intervention (20+)	−0.387***	−9.440**	−17.430***	−2.639***	−0.169***	−0.117***	−0.063**
	(0.094)	(4.000)	(6.316)	(0.810)	(0.044)	(0.037)	(0.027)
Intervention (10-19)	−0.129	−4.492*	−7.522	−0.738	−0.056	−0.048	−0.011
	(0.092)	(2.574)	(4.630)	(0.694)	(0.049)	(0.035)	(0.042)
Observations	305	305	305	305	305	305	305

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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$\geqslant$20μg/dL and thus a more intensive intervention; and those who have two tests with 10$\leqslant$BLL$<$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 $\geqslant$10μ g/dL and a second test $\geqslant$5μg/dL but $<$10μg/dL.

Table 5: Effects of an elevated BLL intervention on other outcomes

	(1) Move	(2) Renovated	(3) Property Sold	(4) Applied LeadSafe	(5) Fixed by LeadSafe	(6) Last BLL Test Value	(7) # BLL Tests
Intervention	−0.076*	−0.026	0.001	0.066**	0.072**	2.994***	2.678***
	(0.046)	(0.031)	(0.032)	(0.033)	(0.032)	(0.399)	(0.273)
Observations	373	373	373	373	373	373	373
Intervention (20+)	−0.075	−0.109*	0.122	0.097	0.102	4.891***	5.824***
	(0.100)	(0.059)	(0.079)	(0.064)	(0.064)	(1.319)	(0.759)
Intervention (10-19)	−0.077	−0.007	−0.027	0.058*	0.066**	2.560***	1.959***
	(0.047)	(0.033)	(0.031)	(0.033)	(0.033)	(0.371)	(0.260)
Observations	373	373	373	373	373	373	373
Treat10-19=Treat20+, p value	0.984	0.088	0.059	0.538	0.564	0.087	0.000

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. 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 dependent variables for results presented are constructed as follows: *Move* represents an indicator as to whether the residential address in the first public school record is different from that reported for the last blood lead test; *Renovated* and *Property Sold* are indicators for home renovations and an arm's length sale of a single-family or multi-family parcel within two years after the date of an individual's initial BLL; *Applied LeadSafe* and *Fixed by LeadSafe* are indicators of LeadSafe program application and participation as determined by matching parcels using residential address in the blood lead surveillance data with data provided by LeadSafe Charlotte on all applications and property remediations since 1998; *Last BLL Test Value* and *# BLL Tests* indicate the final BLL value for an individual and the total number of BLL tests recorded.

We obtain a large sample here because we are not restricted to observing an individual as a student in Charlotte-Mecklenburg Schools.

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.

Appendices

A. Background on Effects of Lead Exposure

Several studies document a direct influence of lead on neurological development (Bellinger, 2008; Cecil et al., 2008; Yuan et al., 2006; Meng et al., 2005; Trope et al., 2001). According to a recent assessment by the U.S. EPA, "A number of mechanisms, including changes in neurogenesis, synaptogenesis and synaptic pruning, long term potentiation, and neurotransmitter function have been identified that provide biological plausibility for epidemiologic and toxicological findings of persistent cognitive and behavioral effects that result from Pb exposures during prenatal and early childhood periods" (EPA, 2013).

A large literature across multiple disciplines consistently associates lead exposure with lower cognitive outcomes, 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 assessing the impact of lead on measures of academic performance and achievement in children and young adults.[37]

There also exists a great deal of evidence that lead exposure effects externalizing behaviors such as attention, impulsivity, and hyperactivity in young children (Froehlich et al., 2009; Chen et al., 2007). These behavioral effects translate into 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 assessing the impact of lead on measures of behavioral outcomes.[38]

While EPA (2013) concludes that there is sufficient scientific evidence to determine that lead has a causal effect on cognitive functioning and externalizing behaviors, identification concerns exist since unobserved determinants of cognitive and behavioral outcomes are likely correlated with the degree of childhood lead exposure. Lower housing quality and poor property maintenance are associated with both higher risks of exposure as well as other factors that directly influence development and behavior, such as parenting quality. To address these important identification concerns, most studies include a wide range of covariates measuring individual, family, and community-level characteristics to control for confounding factors which are correlated with lead exposure. Recent research in the economics literature rely on aggregate shocks to the amount of lead in a particular environment to identify causal effects (Reyes, 2015; Rau et al., 2013; Nilsson, 2009; Clay et al., 2014; Ferrie et al., 2012; Troesken, 2008).

B. 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

[37] Table 4-3 on page 4-62 of lists studies assessing the impact of lead on Full Scale IQ (FSIQ); Table 4-9 on page 4-114 lists studies assessing the impact of lead on measures of academic performance and achievement in children and young adults; Table 4-11 on page 4-156 lists studies assessing the impact of lead on measures of attention, impulsivity, and hyperactivity in children; and, Table 4-12 on page 4-179 lists studies assessing the impact of lead on behaviors related to conduct disorders in children and young adults.

[38] Table 4-11 on page 4-156 lists studies assessing the impact of lead on measures of attention, impulsivity, and hyperactivity in children; and, Table 4-12 on page 4-179lists studies assessing the impact of lead on behaviors related to conduct disorders in children and young adults.

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 1 μg/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 10 μg/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.[39] 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>10.

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 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

[39] 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.

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. Furthermore, we restrict siblings to sharing a residence in at least one year based on lead testing addresses or school addresses to avoid the inclusion of siblings based on mother's with children living at more than one residence and to focus our analysis on siblings that lived in the same home.

B.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.

Figure A1: Elevated blood lead level intervention policy of the Children's Environmental Health branch within the North Carolina Department of Health

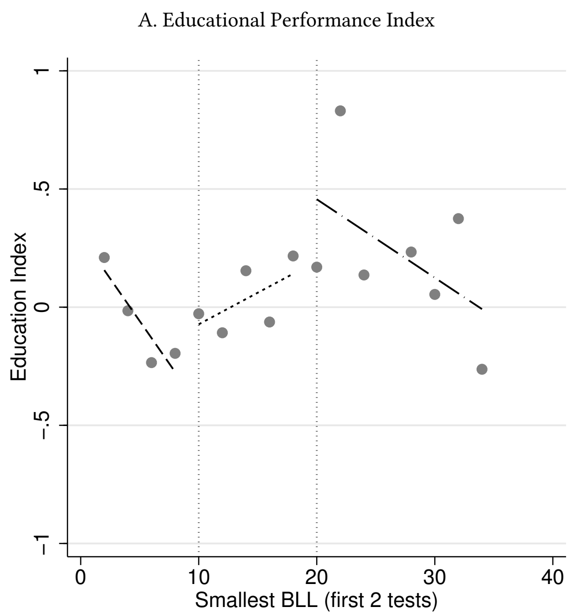
Interpretation of Screening Test Results and Recommended Follow-up

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).

Figure A2: Regression Discontinuity Plots



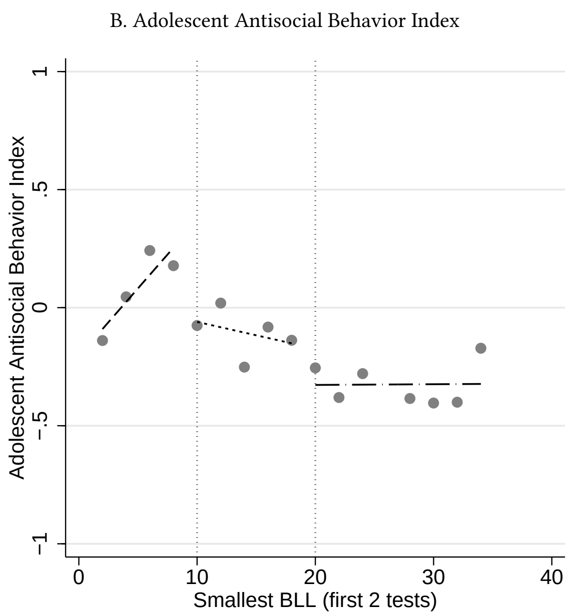


Figure Note: These figures represent basic regression discontinuity plots for our three outcome indices. The sample used for this analysis represents all individuals with at least two BLL tests. The x-axis indicates the smallest BLL for an individual and dots indicate mean outcome index values averaged to BLL intervals that span two BLLs (1-2,3-5,6-7,8-9,10-11,12-13,14-15,16-17,18-19,20-21...). BLL intervals with only one individual are dropped.

Table 1A: Means of education and behavior outcomes

	All Students	Lead Tested	BLL 5-9μg/dL	BLL ⩾10μg/dL
Blood lead level (μg/dL)	4.144	4.220	6.169	13.162
	(3.115)	(3.236)	(1.245)	(7.906)
Education Outcomes				
Reading Test Score (avg 3-5th grade)	−0.030	−0.204	−0.364	−0.477
	(0.965)	(0.956)	(0.934)	(0.912)
Math Test Score (avg 3-5th grade)	−0.033	−0.205	−0.366	−0.432
	(0.973)	(0.953)	(0.921)	(0.911)
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	−0.413
	(0.967)	(0.952)	(0.932)	(0.916)
Math Test Score (avg 6-8th grade)	−0.038	−0.175	−0.324	−0.382
	(0.969)	(0.935)	(0.888)	(0.883)
Repeat a grade (grades 6-9)	0.101	0.142	0.193	0.198
	(0.302)	(0.349)	(0.395)	(0.399)
Adolescent Antisocial Behavior Outcomes				
Total Days Suspended from School (6th-10th grade)	4.34	8.49	11.29	14.41
	(13.39)	(19.85)	(22.88)	(26.80)
Total Days Absent (6th-10th grade)	20.78	30.64	37.23	41.46
	(31.00)	(39.30)	(45.74)	(47.73)
Total School Reported Crimes/Incidents (6th-10th grade)	0.93	1.96	2.44	2.78
	(3.02)	(4.63)	(5.09)	(5.41)
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	930

Means and standard deviations are reported above. 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 1B: Means of demographic, housing, and neighborhood characteristics

	All Students	Lead Tested	BLL 5-9µg/dL	BLL ⩾10µg/dL
Background Characteristics				
Male	0.51	0.51	0.52	0.55
	(0.50)	(0.50)	(0.50)	(0.50)
Minority	0.49	0.60	0.69	0.70
	(0.50)	(0.49)	(0.46)	(0.46)
Stand Alone Residence	0.67	0.65	0.63	0.66
	(0.47)	(0.48)	(0.48)	(0.47)
Year Home Built	1978.67	1970.03	1967.03	1963.96
	(18.09)	(18.66)	(19.06)	(21.45)
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)	0.60	1.12	1.23	1.66
	(1.49)	(1.92)	(2.02)	(2.34)
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	12.82
	(2.40)	(2.49)	(2.34)	(2.45)
Mother Education (years)	13.29	12.69	12.33	12.09
	(2.48)	(2.52)	(2.44)	(2.37)
Birth Weight (ozs)	115.83	113.51	112.54	111.12
	(21.86)	(21.97)	(21.39)	(20.59)
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	40.70	40.23
	(25.11)	(22.79)	(20.74)	(20.46)
CBG Percent in Poverty	0.26	0.40	0.46	0.48
	(0.30)	(0.40)	(0.42)	(0.44)
Observations	153,039	19,731	5,857	930

Means and standard deviations are reported above. 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 A2: Balancing test for missing data indicators

	(1) Intervention (10+)	(2) Intervention (10-19)	(3) Intervention (20+)
School Information Missing	0.041	0.066	−0.033
	(0.071)	(0.070)	(0.055)
Residential Information Missing	−0.044	−0.036	−0.048
	(0.092)	(0.079)	(0.067)
Birth Record Information Missing	−0.018	−0.032	0.026
	(0.050)	(0.051)	(0.041)
F-Stat (p-value)	0.870	0.692	0.798
Observations	373	345	251

* 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 A3: Effects of an elevated BLL intervention on summary index outcomes: *Robustness Checks*

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Regression Discontinuity at 10 BLL		
Intervention	0.096	−0.371
	(0.288)	(0.402)
Observations	704	704
Control for Initial BLL test		
Intervention	0.111	−0.114
	(0.079)	(0.106)
Observations	305	305
Control for Avg BLL (1st 2 tests)		
Intervention	0.112	−0.141
	(0.080)	(0.090)
Observations	305	305
Initial BLL FE		
Intervention	0.095	−0.138
	(0.079)	(0.123)
Observations	305	305
Average BLL FE		
Intervention	0.109	−0.125
	(0.128)	(0.175)
Observations	305	305

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

Regression Discontinuity at 10 BLL: The first panel presents results for a regression discontinuity around the BLL=10 threshold. The sample used for this analysis represents all individuals with the smallest BLL for the the first two tests between 5 and 19 for just those individuals with at least 2 BLL tests. The running variable in this model is a 2nd degree polynomial for each side of the BLL=10 threshold.

Control for Initial BLL Test: The second panel of the table includes the inital BLL tests result as a control in the regression.

Control for Avg BLL Test: The third panel of the table includes the average BLL results (between 1st and 2nd test) as a control in the regression.

Initial BLL FE: The fourth 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.

Average BLL FE: The second row of results presents estimated effects from models that include fixed effects for the average BLL for an individual's first two tests relative to the control group. The fixed effect captures the expected lead exposure for an individual and limits identification to individuals with the same expected lead exposure but vary in the value of BLL between BLL tests. This variation between tests impacts EBLL policy intervention since individuals must obtain two BLL tests $>= 10$ to receive policy intervention.

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 A4: Effects of an elevated BLL intervention on summary index outcomes: *Alternate Control Groups*

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
Control = >10, 5-9		
Intervention	0.134**	−0.182**
	(0.065)	(0.083)
Observations	305	305
Control = >10, 1-9		
Intervention	0.120**	−0.196***
	(0.057)	(0.070)
Observations	464	464
Control = Only one test >10		
Intervention	0.099	−0.159*
	(0.066)	(0.082)
Observations	578	578
Control = at least one test >10		
Intervention	0.094*	−0.186***
	(0.056)	(0.065)
Observations	922	922
Control = initial BLL of 15+		
Intervention	0.160	−0.195
	(0.112)	(0.122)
Observations	202	202
Control = Initial BLL of 8,9		
Intervention	0.087	−0.214**
	(0.072)	(0.092)
Observations	384	384

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

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

Control = $\geqslant$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 $\geqslant$ 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 $\geqslant 10$. 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 >10: The fourth panel of results presents estimated effects from models that define the control group to include anyone with any number of tests as long as only one test was BLL $\geqslant 10$. This control group includes all individuals who did not show up for a confirmatory test as well as those with a second test below the 10μg/dL threshold.

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.

Control = initial BLL of 8,9: The final panel of results presents estimated effects from models that define the control group as those with initial BLL test results just below the 10μg/dL threshold. Only those with test results equal to 8 or 9μg/dL are included in the control group.

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 A5: Effects of 5-9μg/dL BLL intervention on education and behavorial outcomes
Falsification Test

	(1) Education Index	(2) Reading (avg 3-5th)	(3) Math (avg 3-5th)	(4) Repeat Grade (1-5th)	(5) Reading (avg 6-8th)	(6) Math (avg 6-8th)	(7) Repeat Grade (6-9th)
False Intervention (5-9)	−0.025	−0.114***	−0.098***	−0.006	−0.085**	−0.061	−0.034**
	(0.033)	(0.042)	(0.037)	(0.019)	(0.042)	(0.040)	(0.016)
Observations	3,343	2,769	2,778	3,343	2,663	2,668	3,343

	(1) Adolescent Antisocial Behavior Index	(2) Days Suspended (total 6-10th)	(3) Days Absent (total 6-10th)	(4) School Crimes (total 6-10th)	(5) Ever Arrested	(6) Ever Arrested Violent	(7) Ever Arrested Property
False Intervention (5-9)	0.049	1.073	2.839	0.181	0.017	0.005	0.012
	(0.036)	(1.341)	(2.480)	(0.271)	(0.014)	(0.010)	(0.010)
Observations	3,343	3,343	3,343	3,343	3,343	3,343	3,343

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

This table presents our main outcomes from a model comparing students who test twice over the threshold of 5μg/dL but neither test was above 9μg/dL with those who test once over, but then the second test is under. During the time period of our analysis, there was not a significant intervention associated with BLL tests over 5μg/dL but less than 10μg/dL.

Table A6: Effects of an elevated BLL intervention on summary index outcomes for siblings

	(1) Education Index	(2) Adolescent Antisocial Behavior Index
All Siblings		
Sibling of Child (>10 , >10)	0.198	−0.188
	(0.134)	(0.187)
Observations	138	138
Younger Siblings		
Younger Sibling of Child (>10 , >10)	0.112	−0.454
	(0.263)	(0.305)
Observations	74	74
Older Siblings		
Older Sibling of Child (>10 , >10)	−0.190	0.138
	(0.783)	(0.564)
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 A7: 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	15.454	26.429
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(3.995)	(5.667)	(10.152)
<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	−0.517	−0.346
	(0.977)	(0.951)	(0.952)	(0.935)	(0.923)	(0.925)	(0.907)	(0.930)	(0.909)	(0.930)	(0.834)	(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	−0.208	−0.167
	(0.294)	(0.321)	(0.359)	(0.382)	(0.406)	(0.422)	(0.434)	(0.434)	(0.440)	(0.430)	(0.408)	(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	7.169	7.250
	(10.793)	(13.035)	(15.627)	(16.227)	(18.789)	(19.383)	(20.611)	(21.444)	(18.798)	(24.711)	(14.626)	(13.686)
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	23.431	23.893
	(25.251)	(29.017)	(32.830)	(33.032)	(39.222)	(41.563)	(46.933)	(40.708)	(41.220)	(45.996)	(36.207)	(24.293)
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	1.631	1.179
	(2.785)	(3.530)	(3.746)	(3.851)	(4.233)	(4.313)	(4.821)	(4.386)	(3.923)	(4.925)	(3.327)	(2.056)
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)	(0.262)	(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)	(0.199)	(0.000)
Observations	3,015	5,390	6,239	5,137	3,471	2,203	1,357	885	568	1,174	130	28

Means and standard deviations are reported above. 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.