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Children's blood lead and standardized test performance response as indicators of neurotoxicity in metropolitan New Orleans elementary schools

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ABSTRACT

This study analyzes pre-Katrina variation in aggregate student performance and children's blood lead (BPb) in 117 elementary school districts in metropolitan New Orleans. Fourth grade student achievement on Louisiana Educational Assessment Program (LEAP) tests were analyzed as a function of BPb for children 1–6 years old within school districts, controlling for student–teacher ratios, percent of students eligible for a free or discounted lunch, and school racial demography. Measures of performance across subject areas (English Language Arts, Science, Mathematics, and Social Studies) include school Achievement Test Scores (ATS) and indices of agreement and variation in student achievement. ATS are measured on a 5-point scale, corresponding to achievement categories of advanced = 5 to unsatisfactory = 1. Regression results show that median BPb (μg/dL) and percent of children with BPb $\geq$ 10 μg/dL are significantly associated with reductions in test scores across all subjects and depress variation in student performance across achievement categories. These data suggest that assisting children with improved school performance requires alleviation of pre-school Pb exposure and its associated neurotoxic damage. Cost–benefit calculations suggest that it is more cost effective to pay for onetime primary prevention instead of paying continuous expenses focused on reversing neurotoxic damage.

1. Introduction

The topic of this paper is Pb neurotoxicity and its impact on learning achievement in pre-Katrina New Orleans public schools. A critical question concerns how neurotoxicity relates to the learning performance of children within actual schools (May, 2000). Because Pb is metabolized like calcium and stored in the bones, deciduous teeth contain a record of early exposure. Pioneering research by Needleman et al. (1979) involved measuring the amount of Pb accumulated in deciduous teeth and matching the results with assessments by teachers of children's learning behaviors in the classroom, and the topic has evolved rapidly (Needleman, 2004).

Recent studies describe the neurotoxic association between lead exposure of children, usually measured as blood lead (BPb), and learning deficits, generally expressed as intelligence quotient (IQ). IQ is a score derived from several different standardized tests that attempt to measure intelligence. By matching BPb with IQ, researchers have observed a steeper slope in decline of IQ at BPb less than 10 μg/dL compared with the lower slope of decline over the entire range of exposures (Canfield et al., 2003; Jusko et al., 2008; Rothenberg and Rothenberg, 2005). Behavioral disorders are also an important variable in the classroom and neurotoxic effects of Pb exposure in early childhood have been directly associated with disruptive behavior (Needleman et al., 1996, 2002; Wright et al., 2008). Research has further elaborated the role of Pb in school performance. In Ohio, risk of learning failure was identified as being strongly associated with urban youth living in inner cities where high Pb environments and high BPb levels are typical (Boyd et al., 1999). However, among educators it is more typical to find a lack of awareness regarding the neurotoxic affect of early Pb exposure on the learning achievement of children within school districts (Martin, 2008).

Central to this study is an important feature about the pre- and post-Katrina public schools of New Orleans. The Louisiana Educational Assessment Program (LEAP) of high-stakes tests (measuring the mastery of state content standards) was first

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administered to public school students in grades 4 and 8 in Spring 1999 (Louisiana Educational Assessment Program, 2009). In 2003, after recognition of the abysmal failure rates by many public schools, the Louisiana legislature passed a law to create special Recovery School Districts (RSD) administered by the Louisiana Department of Education (Louisiana Recovery School Districts, 2009). The RSD are designed to transform underperforming schools into successful learning places for children. Post-Katrina, after the catastrophic engineering failure resulting in the flooding of New Orleans, all public schools were closed. Most New Orleans public schools were then taken over by the Louisiana Department of Education. Presently, in addition to parochial and private schools, there is a mix of public schools including some remaining under the jurisdiction of the New Orleans Public School system (5 public and oversight of 11 charter schools), while most of the public schools are under state control as Recovery School Districts (30 schools and oversight of about 30 charter schools). The new public schools draw students from all areas of the city. The unique feature of this study is that prior to Hurricane Katrina, 4th grade students in the New Orleans Public School system went to neighborhood schools. The neighborhood school setup provided the opportunity to assemble a spatially matched database by census tracts (i.e., communities or neighborhoods) which included soil lead, blood lead of children 6 years old and younger, and 4th grade student LEAP scores from the neighborhood public schools.

In a previous study of New Orleans schools, the neurotoxic actions of Pb were indicated by elementary students whose depressed Louisiana Educational Assessment Program (LEAP) scores were associated with increased amounts of soil metals (including Pb) accumulated in the exterior soil environments within the school districts (Mielke et al., 2005a; Mielke and Berry, 2007). The current study differs from the previous study in that it focuses on BPb instead of soil metals (including Pb) within school districts. Two databases are used to evaluate the association between Pb exposure and neurotoxic response in this study. First, BPb surveillance results of the Louisiana Childhood Lead Poisoning Prevention Program (LACLPPP), conducted between 2000 until Hurricane Katrina (August 29, 2005) were used. Second, learning achievement as an indication of neurotoxicity was evaluated from standardized test scores of the LEAP 4th grade public elementary school attendees (Louisiana Department of Education, 2008). The purpose of this study is to evaluate the association between BPb in children enrolled in public elementary school districts matched with LEAP performance response as an indicator of Pb neurotoxicity in pre-Katrina metropolitan New Orleans.

2. Methods

2.1. Research design

The dataset is a match of records at the elementary school level. Records include attendance district schools assigned to census tracts, aggregated BPb data from the LACLPPP assigned to census tracts, LEAP score data by subject area (English Language Arts, Science, Mathematics, and Social Studies) for elementary schools, and school demographic data from the National Center for Education Statistics. Matched data are available for 117 elementary schools in metropolitan New Orleans that draw students directly from the local community (or census tract). Our analysis focuses on the 117 district schools where LEAP data and BPb were available. Next, we discuss variable operations and measurements, beginning with two dependent variables (school achievement test scores and distribution of achievement scores), and then two groups of independent variables (school demography and BPb of children in the communities of each of the elementary schools).

2.2. Dependent variables

2.2.1. School achievement test scores

In New Orleans, student mastery of state content standards is measured by the LEAP test (Louisiana Department of Education, 2008). LEAP tests are administered in the spring of the year to 4th and 8th grade students. Competence in four subject areas of English Language Arts, Science, Mathematics, and Social Studies is assessed annually. Student competence is measured categorically as: advanced (a), proficient (p), basic (b), approaching basic (ab), and unsatisfactory (u).

Data on the number of 4th grade students in each achievement category by subject area and elementary school are publicly available. In addition to modeling performance for each category of achievement, we convert frequency data by achievement category for each elementary school, from 1999 to 2003, to a Achievement Test Score (ATS) by

$$\text{ATS} = \frac{5n_a + 4n_p + 3n_b + 2n_{ab} + 1n_u}{N} \tag{2.1}$$

where n_a, n_p, n_b, n_{ab}, and n_u denote the number of 4th grade students classified as advanced, proficient, basic, almost basic, and unsatisfactory, respectively, and $N = n_a + n_p + n_b + n_{ab} + n_u$. The logic of calculation is similar to how a student GPA is calculated where percent scores are turned into grade points that are used to calculate a grade point average. Our school-level ATS range from 1 to 5. ATS are highest for English ($\mu = 2.264$, $\sigma = 0.469$), followed by Social Studies ($\mu = 2.131$, $\sigma = 0.501$), Science ($\mu = 2.129$, $\sigma = 0.502$), and Mathematics ($\mu = 2.101$, $\sigma = 0.502$), with all mean values falling between basic and approaching basic achievement levels.

2.2.2. Indices of ordinal variation (IOV) and consensus (IOC)

In addition to modeling school ATS by subject area, we estimate variation in student achievement by indices of ordinal variation (IOV) and consensus (IOC), i.e., agreement. In the analyses that follow, we test whether BPb in children, adjusting for various school characteristics, increases consensus in student achievement, or compresses the distribution of achievement scores. First, formulae for the IOV and IOC are presented, and then frequency data from one selected elementary school are analyzed to illustrate statistical logic. IOV assesses observed variation in ordinal data against theoretically maximum variation, while preserving category order. Specifically, for c fixed, mutually exclusive, and ordered categories from 1 to c with frequencies $n_1, \ldots, c$, where

$$N = \sum_{i=1}^{c} n_i, \tag{2.2}$$

the index of ordinal variation is given by

$$\text{IOV} = \frac{V}{V_{\max}} \tag{2.3}$$

where

$$V = \sum_{i<j} n_i n_j (j - i), \tag{2.4}$$

the sum is over all pairs of i and j across categories such that $1 \le i < j \le c$, and

$$V_{\max} = (c-1)\left(\frac{N}{2}\right)^2 \tag{2.5}$$

if N is even, or

$$V_{\max} = (c-1)\left(\frac{N+1}{2}\right)\left(\frac{N-1}{2}\right) \tag{2.6}$$

if N is odd (Berry and Mielke, 1992). The complement of IOV is the index of ordinal consensus (IOC), given by

$$IOC = 1 - IOV. \tag{2.7}$$

We illustrate the logic of IOV/IOC statistics with Science score data from one selected school. From 1999 to 2003, 15 students achieved advanced, 89 achieved proficient, 198 achieved basic, 81 achieved approaching basic, and 19 achieved unsatisfactory.

First, using Eq. (2.4),

$$V = (15)(89)(2-1) + (15)(198)(3-1) + \cdots + (81)(19)(5-4) = 74,274.$$

From Eq. (2.5) we derive a theoretically maximum consensus,

$$V_{\max} = (5-1)\frac{(402)^2}{2} = 161,604.$$

Eq. (2.3) yields an index of ordinal variation value of

$$IOV = \frac{74,274}{181,604} = 0.4596,$$

and, the complement, Eq. (2.7), yields an observed ordinal consensus of $IOC = 1 - .4596 = 0.5404$. Therefore, as an example, one of the elementary schools had an ordinal consensus in student Science scores that is 0.5404 of the maximum consensus. The consensus of the distribution of scores among sampled elementary schools by subject area is highest in Science ($\mu = 0.590$, $\sigma = 0.061$), followed by Social Studies ($\mu = 0.566$, $\sigma = 0.058$), Mathematics ($\mu = 0.536$, $\sigma = 0.078$), and English ($\mu = 0.529$, $\sigma = 0.046$).

2.3. Independent variables

2.3.1. School characteristics

Three school-level control variables are used in regression analyses to predict school ATS and IOC: (1) student–teacher ratio, (2) students eligible for a free or discounted lunch, and (3) a Herfindahl index of racial demography. School-level data are from the National Center for Education Statistics, U.S. Department of Education. Student–teacher ratio is measured as the number of students divided by the number of full-time teachers. For elementary schools examined, student–teacher ratios range from 9.09 to 25.85. Percent lunch-eligible is measured as the number of students qualifying for a free or discounted lunch divided by student body size, multiplied by 100. Students are entitled to a free lunch if household income is at or below 130 percent of Social Security Administration poverty levels, and eligible for a discounted lunch if household income is between 130 and at or below 185 percent of Federal poverty levels. Students are automatically enrolled in the National School Lunch Program (NSLP) if they are homeless, a runaway, a migrant child, or enrolled in Head Start on the basis of low-income criteria (U.S. Department of Agriculture, 2008). In our sample of elementary schools, the percentage of lunch-eligible students ranges from 25.16 to 97.10 ($\mu = 79.25$, $\sigma = 17.01$). The racial composition of a student body is measured by the Herfindahl index,

$$H = \sum_{i=1}^{N} s_i^2, \tag{2.8}$$

where s_i is the proportional share of racial group i in an elementary school and N is the number of racial groups (Hirschman, 1964). In 1999, for example, in one selected school we observed a racial composition of 105 (0.185) Black students, 236 (0.415) Hispanic students, 24 (0.042) Asian students, 4 (0.007) Native American students, and 200 (0.352) White students. The Herfindahl race index calculation was

$$H = (0.185)^2 + (0.415)^2 + (0.042)^2 + (0.007)^2 + (0.352)^2 = 0.332.$$

Given a mean Herfindahl race index of 0.78 for the elementary schools sampled, the selected elementary school was racially heterogeneous by comparison. The theoretical logic of this racial homogeneity operation is to test claims in education science on the social and pedagogic benefits of racial diversity in elementary schools (U.S. Commission on Civil Rights, 2006). As a point of interest, of the 117 schools examined, 90 are 50% + minority population and 72 schools are 80% + minority population. So, in the context of metropolitan New Orleans, gains of racial/ethnic diversity is a reasonable outcome to expect. The Herfindhal concentration index is one of many statistical operations available to estimate the racial composition of district schools (i.e., entropy coefficient; dissimilarity index). A maximum value of $H = 1$ indicates a perfectly racially homogeneous school. The minimum value of H, attained when racial groups are of equal number, depends on the number of racial groups in a school (n), and is equal to $1/n$. The n-dependent lower limit must be noted in interpretation. One weakness with the Herfindhal index is that all white, all black, and all Hispanic schools are scored similarly. The achievement implications are likely different by type of racial homogeneity. However, in New Orleans, this logical risk is negligible given the high minority composition of district schools.

2.3.2. Blood lead (BPb) in children

To approximate BPb of children in each elementary school, we spatially matched schools to their census tract and corresponding BPb data on children collected by the LACLPPP from 2000 to 2005. The LACLPPP uses Centers for Disease Control and Prevention protocols on collection, preparation, and analysis of BPb samples (U.S. CDC, 1991). BPb is measured in μg/dL. Each BPb case was geocoded and matched to a census tract, corresponding roughly to a school catchment area. There are 105 catchment areas for 117 schools, including 14 catchment areas with two schools each. Thus, BPb results of 24,327 children were included in the study. The average number of children sampled per catchment area is 242 (with a maximum of 1167 and a minimum of 11 children). For each elementary school, we assigned the median BPb μg/dL of sampled children, the percentage of children sampled with BPb $\geq$ 10 μg/dL (CDC Lead Poisoning Classification IIa) and percentage of children at medically meaningful thresholds of BPb $\geq$ 5 μg/dL from its corresponding census tract. Descriptive statistics for all variables are summarized in Table 1.

3. Results

The median BPb for children across elementary school census tracts was 4.37, and the average percentage of children with BPb equal to or exceeding 10 μg/dL was 11.59 percent. More than 10 elementary schools in our sample were nested in census tracts with the BPb of one-third of children at or exceeding of 10 μg/dL. These BPb results are characteristic of the children living in the community and remain relatively consistent year after year (Mielke et al., 1997, 2005b). Both measures of blood Pb are predictable by observed median soil Pb content (mg/kg) in elementary school census tracts. Fig. 1 is an added variable plot (with linear fit) of median soil lead data (on the x-axis) and percent of children with BPb $\geq$ 10 (on the y-axis) at the census tract scale. Adjusting for socioeconomic characteristics of median housing value, percentage of residents on public assistance, and the percentage of adults (25 years+) with college degree, results

Table 1
Descriptive statistics for dependent and independent variables.

Variable	N	Mean	Std. Dev.	Min	Max
English ATS	117	2.264	0.469	1.540	3.258
Science ATS	117	2.129	0.502	1.391	2.999
Mathematics ATS	117	2.101	0.502	1.225	3.047
Social Studies ATS	117	2.131	0.501	1.337	3.088
English IOC	117	0.529	0.046	0.411	0.637
Science IOC	117	0.590	0.061	0.428	0.729
Mathematics IOC	117	0.536	0.078	0.363	0.813
Social Studies IOC	117	0.566	0.058	0.402	0.736
Percent food eligible	119	79.250	17.014	25.157	97.101
Student-teacher ratio	119	17.236	2.775	9.091	25.846
Herfindahl race index	119	0.777	0.238	0.306	1.000
Median BPb (μg/dL)	119	4.365	1.628	3.000	8.900
Percent BPb $\geq$ 10 (μg/dL)	119	11.592	12.249	0.000	43.370

indicate that the fraction of students exceeding CDC Lead Poisoning Classification IIa increases significantly with soil lead composition ($b = 0.035$, $p = 0.000$), suggesting that BPb levels are locally constituted. Soil samples were collected between February 1998 and January 2000, with 19 samples (on the top 2.5 cm of the soil surface) taken per census tract. The protocol for collection and 1M HNO_3 extraction method is described in previously published research on urban soils (Mielke, 1994; Mielke et al., 1997, 1999, 2000). The Pb content of 5467 surface samples was analyzed with a Spectro ™ Inductively Coupled Plasma Atomic Emission Spectrometer.

Table 2 reports zero-order correlation coefficients for all variables examined. Results show that both measures of BPb are significantly negatively correlated with school-ATS by all subject areas. For example, median BPb is negatively associated with English ATS, Science ATS, Mathematics ATS, and Social Studies ATS. Both measures of BPb are also significantly related to index of ordinal consensus scores by subject area. For example, median BPb is positively associated with English IOC, Science IOC, Mathematics IOC, and Social Studies IOC. IOC correlation results suggest that observed BPb levels appear to significantly compress the distribution of LEAP scores by achievement category. School characteristic variables behave as expected. As the percentage of students in an elementary school eligible for a free or discounted lunch increases, school-level ATS for all subject areas decreases. Similarly, but to a lesser extent, as the number of students per teacher increases, school-level ATS decreases. The most powerful

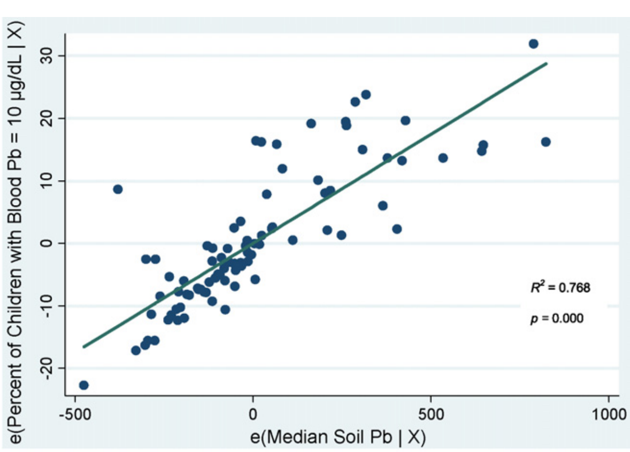

Fig. 1. Added variable scatterplot and linear relationship by census tract data of *n* percent of children with BPb $\geq$ 10 (μg/dL) by median soil Pb content (mg/kg). *Note*: The relationship is adjusted by socioeconomic characteristics of median housing value, percentage of residents on public assistance, and the percentage of adults (25 years+) with college degree.

Table 2
Correlation matrix of student achievement (ATS and IOC by subject area) and predictors.

	English ATS	Science ATS	Mathematics ATS	Social Studies ATS	English IOC	Science IOC	Mathematics IOC	Social Studies IOC	Percent food eligible	Student–teacher ratio	Herfindahl race index	Median BPb (μg/dL)	Percent BPb $\geq$ 10 (μg/dL)
English ATS	1.00												
Science ATS	+.95**	1.00											
Mathematics ATS	+.96**	+.96**	1.00										
Social Studies ATS	+.95**	+.99**	+.96**	1.00									
English IOC	−.53**	−.47**	−.46**	−.47**	1.00								
Science IOC	−.78**	−.76**	−.77**	−.75**	+.75**	1.00							
Mathematics IOC	−.77**	−.78**	−.73**	−.76**	+.74**	+.82**	1.00						
Social Studies IOC	−.55**	−.54**	−.51**	−.56**	+.75**	+.73**	+.86**	1.00					
Percent food eligible	−.68**	−.68**	−.67**	−.65**	+.36**	+.55**	+.56**	+.35**	1.00				
Student–teacher ratio	−.24*	−.31**	−.30**	−.28**	−.08	+.17	+.13	−.00	+.10	1.00			
Herfindahl race index	−.71**	−.78**	−.70**	−.77**	+.45**	+.68**	+.65**	+.47**	+.56**	+.31**	1.00		
Median BPb (μg/dL)	−.63**	−.65**	−.60**	−.64**	+.42**	+.58**	+.55**	+.45**	+.40**	+.18	+.60**	1.00	
Percent BPb $\geq$ 10 (μg/dL)	−.60**	−.63**	−.58**	−.62**	+.41**	+.57**	+.54**	+.47**	+.36**	+.19*	+.56**	+.97**	1.00

Note: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.01$.

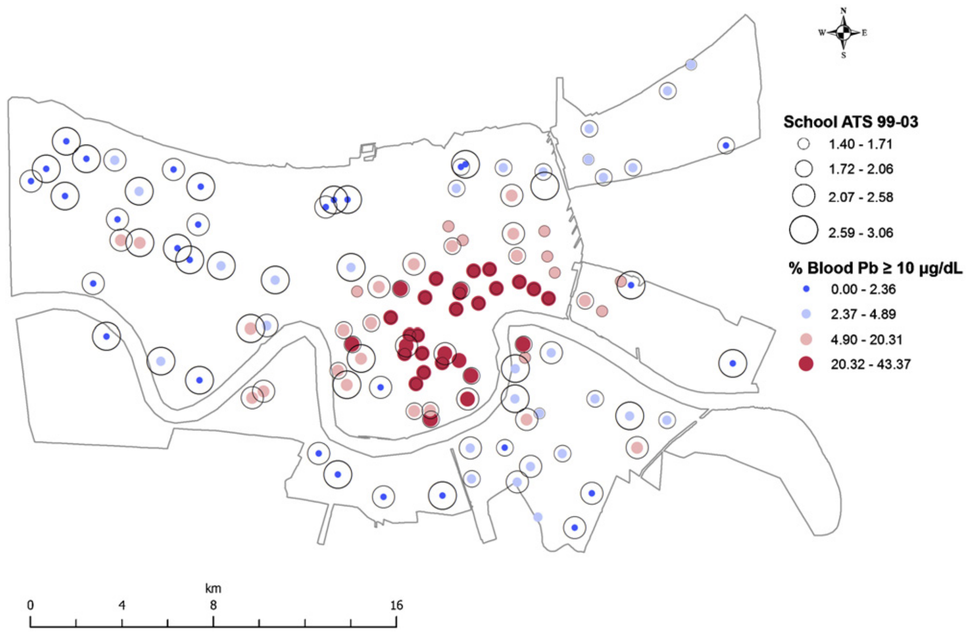

Fig. 2. Distribution of the percentage of children with BPb at or above 10 µg/dL and full achievement test scores, or ATS (combination of English Language Arts, Science, Mathematics, and Social Studies) from 4th grade standardized test performance responses associated with the pre-Hurricane Katrina public elementary schools of metropolitan New Orleans.

correlate of both school-level ATS and subject area IOC scores is the Herfindahl race index, estimating the racial homogeneity of the student body.

Spatial analyses corroborate the correlation results. Fig. 2 shows the distribution of the percentage of children with BPb at or above 10 µg/dL and elementary school ATS (combining achievement outcomes in English Language Arts, Science, Mathematics, and Social Studies) from 4th grade standardized test scores. Both BPb and school ATS distribution are divided into quartiles. Blue colored dots reflect a lower percentage of children with BPb levels at or above 10 µg/dL, and red colored dots indicate higher BPb exposure. Each colored dot is encircled by a ring corresponding to school-level ATS. Larger ring sizes indicate higher ATS scores. Geographically, a strong negative correspondence is observed between BPb values and school test outcomes.

Next, we render a series of ordinary least-squares regression models predicting school-level ATS and IOC scores by subject area. The analytic objective is to test whether BPb levels explain student

Table 3

Ordinary least-squares regression models predicting school ATS in English and level of ordinal consensus in student achievement.

	English ATS (Model 1)	English IOC (Model 2)	English ATS (Model 3)	English IOC (Model 4)
Herfindahl race index	−0.584*** (0.153)	+0.0638*** (0.0221)	−0.660*** (0.150)	+0.0650*** (0.0215)
Percent food eligible	−0.0107*** (0.00179)	+0.000315 (0.000258)	−0.0109*** (0.00179)	+0.000323 (0.000257)
Student–teacher ratio	−0.00400 (0.00987)	−0.00425*** (0.00142)	−0.00270 (0.00989)	−0.00437*** (0.00142)
Median BPb (µg/dL)	−0.0820*** (0.0195)	+0.00657** (0.00281)	–	–
Percent BPb ≥ 10 (µg/dL)	–	–	−0.0104*** (0.00250)	+0.0009** (0.000359)
Constant	+4.019*** (0.192)	+0.500*** (0.0277)	+3.799*** (0.196)	+0.519*** (0.0281)
Observations	117	117	117	117
F-ratio	58.08	12.32	57.91	12.60
Root MSE	0.272	0.039	0.273	0.039
R^2	0.675	0.306	0.674	0.310

Note: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$; standard errors in parentheses.

Table 4

Ordinary least-squares regression models predicting school ATS in science and level of ordinal consensus in student achievement.

	Science ATS (Model 1)	Science IOC (Model 2)	Science ATS (Model 3)	Science IOC (Model 4)
Herfindahl race index	−0.848*** (0.146)	+0.103*** (0.0241)	−0.882*** (0.143)	+0.105*** (0.0234)
Percent food eligible	−0.0102*** (0.00171)	+0.000901*** (0.000282)	−0.0103*** (0.00171)	+0.000912*** (0.000280)
Student–teacher ratio	−0.0143 (0.00942)	−0.00184 (0.00155)	−0.0131 (0.00943)	−0.00199 (0.00155)
Median BPb (µg/dL)	−0.0804*** (0.0186)	+0.00859*** (0.00307)	–	–
Percent BPb ≥ 10 (µg/dL)	–	–	−0.0102*** (0.00239)	+0.00118*** (0.000392)
Constant	+4.188*** (0.183)	+0.433*** (0.0302)	+3.972*** (0.187)	+0.458*** (0.0307)
Observations	117	117	117	117
F-ratio	80.38	30.47	80.19	31.06
Root MSE	0.260	0.043	0.260	0.043
R^2	0.742	0.521	0.741	0.526

Note: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$; standard errors in parentheses.

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Table 5
Ordinary least-squares regression models predicting school ATS in mathematics and level of ordinal consensus in student achievement.

	Mathematics ATS (Model 1)	Mathematics IOC (Model 2)	Mathematics ATS (Model 3)	Mathematics IOC (Model 4)
Herfindahl race index	−0.649*** (0.170)	+0.138*** (0.0301)	−0.678*** (0.166)	+0.139*** (0.0292)
Percent food eligible	−0.0114*** (0.00199)	+0.00104*** (0.000352)	−0.0116*** (0.00198)	+0.00105*** (0.000348)
Student–teacher ratio	−0.0189* (0.0110)	−0.00132 (0.00194)	−0.0177 (0.0110)	−0.00155 (0.00192)
Median BPb (μg/dL)	−0.0746*** (0.0217)	+0.0122*** (0.00384)	–	–
Percent BPb ≥ 10 (μg/dL)	–	–	−0.00961*** (0.00278)	+0.00170*** (0.000487)
Constant	+4.157*** (0.213)	+0.318*** (0.0377)	+3.955*** (0.217)	+0.353*** (0.0382)
Observations	117	117	117	117
F-ratio	52.09	34.09	52.17	35.17
Root MSE	0.302	0.054	0.3022	0.053
R^2	0.650	0.549	0.651	0.557

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$; standard errors in parentheses.

Table 6
Ordinary least-squares regression models predicting school ATS in Social Studies and level of ordinal consensus in student achievement.

	Social Studies ATS (Model 1)	Social Studies IOC (Model 2)	Social Studies ATS (Model 3)	Social Studies IOC (Model 4)
Herfindahl race index	−0.904*** (0.156)	+0.0777*** (0.0279)	−0.928*** (0.152)	+0.0749*** (0.0268)
Percent food eligible	−0.00918*** (0.00183)	+0.000315 (0.000326)	−0.00930*** (0.00182)	+0.000318 (0.000321)
Student–teacher ratio	−0.00781 (0.0101)	−0.00370** (0.00179)	−0.00652 (0.0100)	−0.00390** (0.00177)
Median BPb (μg/dL)	−0.0769*** (0.0199)	+0.00918** (0.00355)	–	–
Percent BPb ≥ 10 (μg/dL)	–	–	−0.0101*** (0.00254)	+0.00143*** (0.000449)
Constant	+4.024*** (0.196)	+0.505*** (0.0349)	+3.812*** (0.199)	+0.534*** (0.0351)
Observations	117	117	117	117
F-ratio	66.55	11.82	67.29	12.98
Root MSE	0.278	0.050	0.277	0.049
R^2	0.704	0.297	0.706	0.317

Note: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$; standard errors in parentheses.

performance on standardized tests, adjusting for school demographic characteristics. Table 3 reports four models of English ATS and IOC scores, with the two BPb variables taking turns as regressors of school performance outcomes. All things held equal, median BPb decreases English ATS scores, and increases English IOC scores. The same is true of percent of children with BPb ≥ 10 (μg/dL). Other notable results in Table 3 are that for perfectly racially homogenous schools (Herfindahl index = 1), we observe a reduction in English ATS of about two-thirds of a point, on a point scale of 1–5. Interestingly, student–teacher ratio has a negligible effect on English ATS, but is significantly associated with a reduction in English IOC scores. Meaning, ceteris paribus, a reduction in the number of students per teacher does not significantly alter average performance in English, but does significantly increase variation in student performance.

With regard to student achievement in Science (Table 4), Mathematics (Table 5), and Social Studies (Table 6) we find similar results. Whether one regresses Science, Mathematics or Social Studies ATS or IOC scores on median BPb or percent of children with BPb ≥ 10 μg/dL we observe statistically significant effects. Median BPb, for example, is associated with a reduction in ATS in Science, Mathematics, and Social Studies and increases IOC scores across subjects. Overall, the variance explained in ATS outcomes by our suite of variables across all models executed ranges from $R^2 = 0.650$ to $R^2 = 0.741$, and $R^2 = 0.297$ to $R^2 = 0.557$ for IOC scores.

Next, we compute marginal effects or elasticities of achievement outcomes for both ATS and IOC scores across subject areas at selected point (or percentile rank) estimates of the percentage of children with BPb ≥ 10 μg/dL. Elasticities are calculated with control variables fixed at their sample means, deriving the expected percent decline in achievement outcomes by subject area. Fig. 3 graphically displays marginal effects. The elasticity of subject ATS vs. percent of students with BPb ≥ 10 μg/dL is displayed on the left *y*-axis, and the elasticity of subject IOC vs. percent of students with BPb ≥ 10 μg/dL is on the right *y*-axis. Overall, at around the 50th percentile (roughly 5 percent of children with BPb ≥ 10 μg/dL) we observe a steep downturn in ATS and a similarly sloped uptick in IOC scores. At 15 percent of children with BPb ≥ 10 μg/dL (the 70th percentile in our sample space), we observe a 7.0–7.3 percent reduction in school-level ATS, and a 2.5–4.7 percent increase in ordinal consensus across all subject areas. In Table 7 we also provide regression analyses of more toxicologically meaningful thresholds in the BPb distribution, including the percentage of children at or above 2 μg/dL and the percentage of children at or above 5 μg/dL in each census tract. Across all subject areas, we observe significant negative associations between percentage of children at or above 5 μg/dL and test performance.

Table 8 is a contingency table reporting frequency statistics on the distribution of students scoring advanced (*a*), proficient (*p*), basic (*b*), approaching basic (*ab*), and unsatisfactory (*u*) by low ($P_{0.25}$), middle ($P_{0.50}$), and high ($P_{0.75}$) median BPb levels for English, Mathematics, Science, and Social Studies 4th grade LEAP tests. Results indicate a moderately strong negative association between blood lead levels and the distribution of test scores. For example, compared with schools in the 75th percentile on median BPb levels (5.7 μg/dL), schools in the 25th percentile (3.0 μg/dL) have higher fractions of students in advanced and proficient categories of achievement and significantly lower fractions of students in unsatisfactory and approaching basic categories. This statistical pattern persists across subject areas. Nonparametric statistics of association, including gamma and (the more conservative) Somers' d_{yx} reinforce the argument. For the data in Table 8, the ordinal association between median BPb and student achievement for the subject area of English is $\gamma = -0.399$ and $d_{yx} = -0.295$; for the subject area of Mathematics, $\gamma = -0.425$ and $d_{yx} = -0.306$; for the subject area of Science, $\gamma = -0.500$ and $d_{yx} = -0.363$; and for the subject area of Social Studies, $\gamma = -0.470$ and $d_{yx} = -0.340$.

Table 7
Ordinary least-squares regression models predicting school ATS in English Language Arts, Science, Mathematics, and Social Studies.

	English ATS (Model 1)	English ATS (Model 2)	Science ATS (Model 3)	Science ATS (Model 4)	Math ATS (Model 5)	Math ATS (Model 6)	Social ATS (Model 7)	Social ATS (Model 8)
Herfindahl race index	−0.584*** (0.155)	−0.898*** (0.145)	−0.787*** (0.147)	−1.102*** (0.137)	−0.593*** (0.172)	−0.888*** (0.157)	−0.841*** (0.157)	−1.145*** (0.144)
Percent food eligible	−0.00976*** (0.00181)	−0.0105*** (0.00197)	−0.00918*** (0.00171)	−0.00964*** (0.00186)	−0.0105*** (0.00200)	−0.0110*** (0.00213)	−0.00818*** (0.00183)	−0.00858*** (0.00197)
Student–teacher ratio	−0.00363 (0.00980)	−0.00470 (0.0105)	−0.0139 (0.00924)	−0.0149 (0.00992)	−0.0185* (0.0108)	−0.0194* (0.0114)	−0.00737 (0.00989)	−0.00836 (0.0105)
Percent BPb ≥ 5 (μg/dL)	−0.00721*** (0.00164)	–	−0.00751*** (0.00155)	–	−0.00696*** (0.00181)	–	−0.00728*** (0.00165)	–
Percent BPb ≥ 2 (μg/dL)	–	−0.00850 (0.00520)	–	−0.0117** (0.00492)	–	−0.0102* (0.00563)	–	−0.0118** (0.00519)
Constant	+3.828*** (0.193)	+4.642*** (0.460)	+3.993*** (0.182)	+5.069*** (0.435)	+3.976*** (0.213)	+4.918*** (0.498)	+3.835*** (0.195)	+4.909*** (0.459)
Observations	117	117	117	117	117	117	117	117
F-ratio	59.21	48.14	84.47	69.65	53.96	46.53	69.86	59.26
Root MSE	0.27057	0.28956	0.25512	0.2738	0.29889	0.31342	0.27285	0.28895
R^2	0.679	0.632	0.751	0.713	0.658	0.624	0.714	0.679

Note: $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$; standard errors in parentheses.

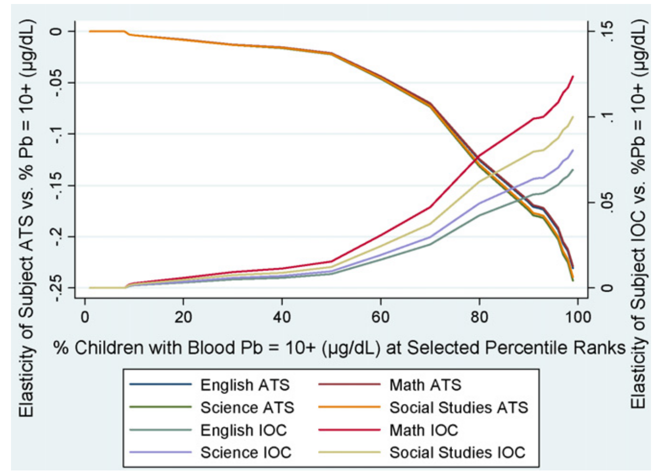

Fig. 3. Elasticities of ATS and IOC scores by subject area vs. percentage of children with BPb ≥ 10 (μg/dL) at selected percentile ranks, conditioned by school racial demography, student–teacher ratio and percent of students eligible for discounted or free lunch.

Table 9 reports least-squares regression models predicting the percentage of students in cumulative achievement categories of advanced, advanced plus proficient, approaching basic plus unsatisfactory, and unsatisfactory. Parameter estimates summarize the expected change in the percentage of students falling into cumulative achievement categories for both unit and standard deviation shifts in predictors. Results corroborate the main hypotheses of the manuscript—ceteris paribus, an increase in BPb levels in children is associated with a decrease in student achievement and a tightening of the distribution of achievement scores. Results show that a unit change in median BPb levels increases the percentage of children in the category of Unsatisfactory achievement by 3.8 (95% CI, 2.2–5.5), and decreases the percentage of the children below Basic achievement by 3.35 (95% CI, 1.6–5.1). Similarly, adjusting for school racial composition, student poverty, and teacher–student ratios, a standard deviation increase in median BPb is associated with a 6.2 unit increase in the percentage of students scoring unsatisfactory in a LEAP test subject area, and a 1.11 unit increase in the percentage of students scoring Proficient or higher on a subject test. Interestingly, results show that going from a perfectly racially diverse school to a perfectly racially homogenous school increases the percentage of children in Unsatisfactory achievement by 32.49 (95% CI, 19.7–45.3).

4. Discussion and conclusions

Children are susceptible to Pb absorption and its neurotoxic effects during periods of prenatal development and crawling stages 12–24 months (Bearer, 2000; Cohen Hubal et al., 2000; Manton et al., 2000). However, the greatest Pb susceptibility appears in children who exhibit an increase of BPb between ages 2 and 6 years; in that case BPb at 6 years is more strongly associated with negative cognitive and behavioral outcomes than BPb at 2 years of age (Hornung et al., 2009). Lead in the bones may be remobilized back into circulation at times of stress and tension, such as pregnancy (Ettinger et al., 2009), illness, life events (i.e., test taking), and aging (Weuve et al., 2009). Assessment of neurotoxic risk requires evaluation of multiple issues including parental support, student preparedness, teacher skills, and institutional infrastructures (Weiss et al., 2008). Included in the panoply of factors, we observe that BPb is a more powerful predictor of student performance than poverty (offset with free or discounted lunch) and class size. Although tangential to our analysis, the results indicate a strong positive association between

Table 8
Percent of advanced (*a*), proficient (*p*), basic (*b*), approaching basic (*ab*), and unsatisfactory (*u*) student scores as low (0.25), middle (0.50), and high (0.75) median BPb levels for English Language Arts, Mathematics, Science, and Social Studies 4th grade LEAP tests.

	a	*p*	*b*	*ab*	*u*	*n*
English						
$P_{0.25}$	291 (1.40)	2797 (13.44)	8819 (42.39)	5474 (26.31)	3424 (16.46)	20,805 (100.00)
$P_{0.50}$	144 (1.71)	872 (10.38)	2883 (34.31)	2229 (26.52)	2276 (27.08)	8,404 (100.00)
$P_{0.75}$	20 (0.11)	625 (3.55)	4062 (23.07)	5268 (29.92)	7631 (43.34)	17,606 (100.00)
Mathematics						
$P_{0.25}$	406 (1.95)	2351 (11.30)	8293 (39.85)	4769 (22.92)	4989 (23.98)	20,808 (100.00)
$P_{0.50}$	92 (1.10)	529 (6.30)	2660 (31.67)	1976 (23.53)	3142 (37.41)	8,399 (100.00)
$P_{0.75}$	21 (0.12)	338 (1.92)	3465 (19.69)	4213 (23.94)	9559 (54.32)	17,596 (100.00)
Science						
$P_{0.25}$	325 (1.56)	2020 (9.71)	8323 (40.02)	7023 (33.77)	3108 (14.94)	20,799 (100.00)
$P_{0.50}$	81 (0.96)	496 (5.90)	2348 (27.92)	3104 (36.90)	2382 (28.32)	8,411 (100.00)
$P_{0.75}$	23 (0.13)	181 (1.03)	2560 (14.54)	6470 (36.74)	8374 (47.56)	17,608 (100.00)
Social Studies						
$P_{0.25}$	197 (0.95)	2032 (9.77)	9475 (45.53)	5127 (24.64)	3978 (19.12)	20,809 (100.00)
$P_{0.50}$	46 (0.55)	524 (6.24)	2853 (33.98)	2201 (26.21)	2772 (33.02)	8,396 (100.00)
$P_{0.75}$	7 (0.04)	267 (1.52)	3428 (19.48)	4631 (26.32)	9265 (52.65)	17,598 (100.00)

Note: Row percentages are in parentheses.

Table 9
Ordinary least-squares regression models predicting the percentage of students in cumulative achievement categories.

	Percent *a*	$bStd_x$	Percent $a+p$	$bStd_x$	Percent $ab+u$	$bStd_x$	Percent *u*	$bStd_x$
Herfindahl race index	-1.017^{***} (0.348)	−0.242	-8.583^{***} (2.151)	−2.042	33.462^{***} (6.791)	7.962	32.49^{***} (6.479)	7.732
Percent food eligible	-0.0597^{***} (0.00406)	−1.020	-0.275^{***} (0.0251)	−4.691	0.442^{***} (0.0794)	7.550	0.262^{***} (0.0757)	4.481
Student–teacher ratio	−0.00595 (0.0224)	−0.266	−0.128 (0.139)	−0.3502	0.566 (0.437)	1.544	0.424 (0.417)	1.157
Median BPb μg/dL	−0.00609 (0.0443)	−0.010	-0.682^{***} (0.274)	−1.1101	3.351^{***} (0.865)	5.433	3.811^{***} (0.826)	6.202
Constant	6.520^{***} (0.436)		41.382^{***} (2.696)		-24.606^{***} (8.509)		-37.22^{***} (8.119)	
Observations	117		117		117		117	
R^2	0.790		0.765		0.683		0.659	

Note: $^{***}p<0.01$; $^{**}p<0.05$; $^{*}p<0.1$; standard errors in parentheses; $bStd_x$ = *x*–standardized coefficient.

BPb and percent of African–American students. This finding supports a previous study on the human geography of Pb contaminated environments and raises questions concerning the issue of environmental justice of the children living in New Orleans (Campanella and Mielke, 2008). Although not the focus of our investigation, our results also show that increased racial diversity of the student body is associated with improved test scores.

Kozol (2005) described disparities in funding and many school characteristics between inner-city and suburban school districts in the U.S. The findings of this study suggest another disparity—school underperformance as a function of environmental Pb accompanied by neurotoxity. As the percentage of Pb poisoned children increases within a community, school-level test performance decreases and variation in student performance compresses. The results are consistent with previous findings about the trend of elevated Pb on inner city elementary school properties compared with elementary school properties in outer-city locations (Higgs et al., 1999). Also, the results are consistent with findings about the association between multiple metals, including Pb, in soils of attendance districts and learning achievement at schools in the same districts of New Orleans (Mielke et al., 2005a). Polluted soils in New Orleans also contain a coexisting suite of exotic chemicals that may play a role in neurotoxicity of children (Mielke et al., 2004; Wang et al., 2004). In New Orleans, as shown in Fig. 1, soil Pb and BPb are strongly associated, further supporting the findings between the current results on BPb and school academic achievement and the previous study on soil Pb accumulation and learning achievement (Mielke et al., 2005a,b; Mielke and Berry, 2007). In addition, soil and associated dust is an important pathway for Pb exposure (Laidlaw et al., 2005; Mielke and Reagan, 1998). Compounding the Pb problem, New Orleans public water supplies are treated with silicofluoride. When silicofluoride is combined with other water treatment disinfectants they are implicated in corrosion of plumbing systems resulting in elevated BPb (Maas et al., 2007). In addition, multiple negative effects of fluorides are associated with changes in brain biochemistry and IQ (Coplan et al., 2007; Tang et al., 2008).

In this study the regression coefficients among median BPb and ATS in English, Science, Mathematics and Social Studies range from $b=-0.075$ to $b=-0.082$ ($p<0.01$), indicating that an increase in median BPb of 1 μg/dL reduces school-ATS by about one-tenth of an ATS point. In the context of a high stakes testing system, with potentially severe costs to teaching and administrative staff for student underperformance, the causes of childhood Pb poisoning must be addressed to improve school learning achievement of children in New Orleans.

These findings suggest important policy tradeoffs when considering the optimal course of action to improve achievement among inner-city elementary schoolchildren. Given the noted current emphasis on testing outcomes, school districts are constantly seeking cost-effective means to increase student performances. Additional school time, increased investment in teachers and technologies, as well as additional school choice are all posited as potential remedies for traditionally low-performing schools and cohorts. Many involve sizable costs. Yet the above results suggest that the environment itself may shape student performance, thus creating even greater and potentially more costly hurdles for performance-enhancing investments to overcome.

Economic theory suggests that the first-best solution to suboptimal outcomes is to address the source of the problem, e.g. the seminal work by Pigou (1946). Attempting to overcome the

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eventual outcomes by indirect means is virtually always a second-best solution. In the present case, such a first-best solution indicates that school districts should consider mitigating the Pb pollution problem as a potential direct means to improve student performance, rather than deal with the lead-tainted aftermath with second-best means. As an example, lower pupil-per-teacher ratios have been a traditional remedy for low performance, with greater instructor time and attention per pupil leading to better learning outcomes. Yet this solution accepts the Pb problem as a given, and may not be as cost effective a means to improve student outcomes as Pb remediation. Indeed, this paper's results find that Pb exposure is a more powerful predictor of student performance than class size, underscoring the potential importance of first-best direct policy considerations.

The common metric, however, that most influences policy considerations is the relative cost (and thus cost-effectiveness) of policy instruments. Teacher investment strategies, while not influencing student performance as much as Pb levels, may be a cheaper means to attain performance goals. Yet such cost considerations only further highlight the potential cost-effectiveness of potential remediation strategies. Remediation strategies can provide long-term achievement improvements for many cohorts of disadvantaged children with a single upfront investment. In contrast, the traditional teacher-oriented strategy implies a stream of costs over time to provide beneficial lower pupil–teacher ratios for each successive student cohort, which could be summarized in a single present discounted value. While future investments will be appropriately discounted in such a calculation, the expense stream suggests that the traditional approach may in fact be relatively costly when compared to one-shot remediation.

To provide an initial indication of the relative costs of each strategy, we use the results from the statistical analysis above to determine a benchmark cost for ATS improvement, which helps estimate the additional number of teachers and consequent increase in funding necessary to reduce student–teacher ratio to achieve such an improvement. This annual spending can then be discounted over an extended period to yield a single net present value estimate of necessary ongoing teaching investments required for the desired increase. This net present value will in turn effectively set a cost ceiling for a contrasting lead remediation effort that would yield the same ATS effect, suggesting the relative viability of a remediation strategy vs. a teacher investment strategy.

We first establish a target ATS improvement of 0.10, or one-tenth of a percentage point (corresponding to the measured loss in ATS from lead exposure). Averaging the coefficients for English, Science, Math, and Social Studies coefficients for student–teacher ratio effects on ATS, which themselves range from −0.0078 to −0.189, yields an overall benchmark coefficient of −0.0113. To achieve the noted target ATS increase of 0.10 thus requires an increase in student–teacher ratio of approximately 8.8 from a mean of 17.2. Given a median school size of 550.7 students, the average representative school requires 32 teachers. Attaining the ATS goal thus necessitates an extra 33.6 teachers, each at an annual cost of $39,130 (Louisiana Department of Education, Division of Education Finance). Assuming a discount rate of 5%, the present discounted value of this teacher investment is thus $26,295,360 per school through a literal doubling of the number of teachers to halve the student–teacher ratio. This figure effectively sets a rough cost ceiling for a single-shot, one-time lead remediation investment to reduce average BPb levels by 1.3 μg/dL from a mean of 4.37, leveraging an average coefficient of −0.0785. Based on this teacher investment cost, the total cost for the 117 schools is more than $3.0 billion. Given current technologies, remediation efforts such as $225–$290 million to emplace clean soil on 40% of New Orleans census tracts with a median of >400 mg/kg (Mielke et al., 2006a) are likely to cost considerably less than this ceiling, suggesting that lead remediation may indeed be relatively more cost-efficient than teacher investment strategies for increasing student achievement to the target level.

The precise quantitative tradeoff of strategies is the subject of current work and will depend on a variety of factors, including BPb elasticities relative to remediation investments as well as the choice of the discount rate. Political pressures suggest emphases on current cohorts, implying a high discount rate and the relatively greater attractiveness of ongoing instructor investments given such strategies' higher early net benefits vs. one-shot remediation's high early costs. Again, though, as indicated above by both theory and cost benchmark estimates, first-best policy approaches are likely to be highly cost-effective relative to second-best alternatives.

Also, we seek to understand how the Recovery School Districts—RSD instituted after Hurricane Katrina (as described in the Introduction), impact school performance. Have the improvements been achieved by mixing that the poorest performing students with the better performing students? Is there evidence that childhood lead poisoning and accompanying neurotoxicity problems described in this study continue to hinder learning achievements in the RSD of New Orleans?

The results of this study support recent calls for lowering BPb action levels from 10 to less than 5 or, even 2 μg/dL (Gilbert and Weiss, 2006; Min et al., 2007), and increased emphasis on primary Pb prevention to protect children from the effects of neurotoxicity (Bellinger, 2008; Rogan et al., 2001). Analyzing achievement outcomes as a function of the percentage of children at or below 5 and 2 μg/dL in Table 7, show that ATS in all subject areas are statistically sensitive to the presence of children at or above these lower threshold levels.

If fluoridation of water supplies increases corrosion of Pb from plumbing systems resulting in increased BPb, multiple brain chemistry effects, and decreased IQ, then eliminating fluoridation is a relatively straight forward step to decrease BPb, reduce neurotoxic insult, and avoid IQ deficits (Coplan et al., 2007; Maas et al., 2007; Tang et al., 2008). Needleman (2004) advocates abatement of Pb-based paint. Because of the customary use of power sanders, experience with Pb-paint abatement in New Orleans has been a disaster for children and their families (Mielke et al., 2001). Measures to prevent exacerbating contamination by the release of Pb from layers of paint must be rigorously addressed to avoid additional Pb accumulation in the interior and exterior environment. It is essential to acknowledge that Pb in the exterior environment of New Orleans was the result of the U.S. nationwide use of millions of tons of Pb in paint, gasoline and other sources (Mielke et al., 2008). The Pb contamination of exterior soils has been documented in many inner-cities (Laidlaw MAS and Filippelli, 2008). Precedence for primary prevention from polluted soils was established by the Norwegian government where soils on sites intended for children's play are tested and remediated if necessary at all daycare centers, elementary schools and parks (Ottesen et al., 2008). In New Orleans a pilot project involving landscape covering of Pb polluted soil (>400 mg/kg) with low Pb sediments (~10 mg/kg) abundantly available from the Mississippi River shows promise as a method for alleviating childrens' exposure to Pb (Mielke et al., 2005a, 2006a,b). The key to reducing Pb neurotoxicity in children is to prevent exposure to Pb in the first place.

Conflict of interest

No conflict of interest.

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