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Lead exposure and educational proficiency: moderate lead exposure and educational proficiency on end-of-grade examinations

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Abstract

Purpose—To investigate and quantify the impact of moderate lead exposure on students' ability to score at the "proficient" level on end-of-grade standardized tests.

Methods—We compared the scores of 3757 fourth grade students from Milwaukee, Wisconsin, on the Wisconsin Knowledge and Concepts Exam (WKCE). The sample consisted of children with a blood lead test before age 3 years that was either unquantifiable at the time of testing (<5 μg/dL) or in the range of moderate exposure (10–19 μg/dL).

Results—After controlling for gender, poverty, English language learner status, race/ethnicity, school disciplinary actions, and attendance percentage, results showed a significant negative effect of moderate lead exposure on academic achievement for all 5 subtests of the WKCE. Test score deficits owing to lead exposure were equal to 22% of the interval between student categorization at the "proficient" or "basic" levels in Reading, and 42% of the interval in Mathematics.

Conclusions—Children exposed to amounts of lead before age 3 years that are insufficient to trigger intervention under current policies in many states are nonetheless at a considerable educational disadvantage compared with their unexposed peers 7 to 8 years later. Exposed students are at greater risk of scoring below the proficient level, an outcome with serious negative consequences for both the student and the school.

Keywords

Lead poisoning; Lead exposure; Childhood; School; Testing; Environmental pollutants; Environmental pollution; Environmental policy

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Childhood lead exposure has been recognized as a major public health issue for over a century. Lead exposure is associated with a wide variety of negative health impacts [1], including protracted physical development and smaller stature [2,3], gastrointestinal disorders [4], lower cognitive function [5–7], antisocial behavior and delinquency [8–13], and in severe cases death [14]. The preponderance of studies demonstrate a consistent albeit modest effect of early childhood lead exposure on cognitive function, often measured by intelligence quotient (IQ) tests [15–19]. Partly because IQ test scores are a familiar measure with proven sensitivity, the association of early life lead exposure with IQ scores has been frequently used in risk analyses and for defining risk levels [1]. Although IQ scores are often statistically correlated with academic and professional success in life, until recently few

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studies have investigated the relationship of lead exposure with more direct educational outcomes such as end-of-grade examinations, which can deterministically influence students' academic trajectories.

School achievement tests have taken on increasing importance in the United States following federal policies that evaluate schools and teachers according to the performance of students on standardized tests administered by each state. The assignment of proficiency categories based on students' scores is emphasized. Schools are required to achieve target percentages of children performing at or above the “proficient” level in reading and math. Schools failing to meet benchmarks risk cuts to funding or closure, making these tests a high-stakes outcome for students, schools, and their communities. The extent to which lead exposure is negatively associated with performance on standardized tests has important implications for American educational policy, as well as public health.

The upper Midwest of the United States, which includes Wisconsin, has a relatively high risk of lead exposure. According to surveillance conducted by the Wisconsin Childhood Lead Poisoning Prevention Program (WCLPPP), in 2006 the statewide prevalence of lead exposure over the level of concern at the time (blood lead level [BLL] ≥10 μg/dL) was 2.6% for tested children under 2 years of age; more than twice the national prevalence. Approximately 5% of children who entered the Wisconsin public school system in 2006 had at least one test result above the level of concern [20]. Despite this high prevalence, state public health interventions in Wisconsin and many other states are currently mandated only for children with elevated BLL defined as 20 μg/dL or greater. There are neither state-mandated interventions nor secondary prevention efforts targeted to children with BLLs that are considered elevated but less than the 20 μg/dL threshold, although some municipalities and counties provide resources. In 2012, the Centers for Disease Control and Prevention (CDC) accepted the recommendation of the Advisory Committee on Childhood Lead Poisoning Prevention [21], and replaced the previous level of concern (10 μg/dL) with a new reference level calculated every 4 years as the 97.5th percentile of BLLs in in the two most recent National Health and Nutrition Examination Survey datasets. This change was made in response to an accumulation of evidence suggesting that there is no safe level of lead exposure [22], with the effect of increasing the number of children that the CDC considers at risk for negative consequences of lead exposure. The present study examines the educational impact of lead exposure, in terms of meeting or failing to meet the “proficient” level on an end-of-grade examination, for children with BLL test results that are elevated but below the threshold for mandated intervention (20 μg/dL).

Methods

We used WCLPPP data to select children from Milwaukee with a BLL test of 10 μg/dL or greater and less than 20 μg/dL before the age of 3. We compared these children having moderately elevated BLL with those with a blood lead test before age 3 but with BLL considered unquantifiable by the Wisconsin State Laboratory of Hygiene (WSLH) at the time of testing (<5 μg/dL). We examined data from children who resided in Milwaukee at the time of their blood test owing to sample size considerations: In addition to being the largest city in Wisconsin, Milwaukee has the highest prevalence of elevated BLLs in children (6.1%) of any municipality in the state [20]. The protocol for this study was approved by the University of Wisconsin–Madison Education Research Institutional Review Board.

Blood lead levels

In 2006, approximately 20% of Wisconsin children under 6 years of age had their blood lead levels tested. Many parents have their children tested voluntarily; however, Wisconsin mandates lead screening for children enrolled in Medicaid and Women, Infants, and Children at their 1st and 2nd birthdays. Sixty-seven percent of children tested in Wisconsin in 2006 were enrolled in one of those programs. Health care providers are required by Wisconsin Administrative Code (HFS 181) to report BLL results to WCLPPP, or to direct the analyzing laboratories to do so. Children in Wisconsin have their blood drawn in clinics, doctor's offices, and hospitals, and their samples are tested by a number of different laboratories. There is substantial variation in the limits of quantification established by individual laboratories. The WSLH, which analyzes more than one quarter of all samples, established a limit of quantification of 5 μg/dL for all blood lead analysis before 2000. Although many laboratories, including the WSLH, are currently able to reliably test below this level, we use it to anchor the low end of the quantifiable lead exposure spectrum in our study because more than half of the BLL results in our sample were tested during this period, many at the WSLH. Our definition of "not exposed" is based on the WSLH limits of quantification at the time of testing, which is also the current CDC reference level [22].

Academic performance

The Wisconsin Knowledge and Concepts Examination (WKCE) is a Wisconsin standardized examination administered to public school students in grades 3 through 8 and 10. Every grade is tested on Mathematics and Reading; in 4th, 8th, and 10th grade students are also tested on Language Arts, Social Studies, and Science. The 4th-grade WKCE is one factor in deciding whether individual students advance to 5th grade [23]. The 4th-grade examination was selected for study, because it is the most comprehensive and high-stakes exam given during the elementary years. Students receive a raw score in each subject area based on the number of questions answered correctly, which is converted to a scaled score intended to maintain a similar distribution of scores across multiple years. The scaled scores are the primary score of interest to Wisconsin educators and policymakers to determine whether schools are meeting federal standards; for that reason, we conducted our analyses using the scaled scores.

Study sample construction

Our sample was constructed by combining Milwaukee Public Schools (MPS) records of academic performance with BLL data maintained by WCLPPP. The sample consisted of children who met the following eligibility criteria: (1) Born between January 1,1996, and December 31, 2000; (2) BLL tested by capillary or venous test before their 3rd birthday and results reported to WCLPPP; (3) Milwaukee address at the time of one or more blood lead tests; and (4) confirmed by the Wisconsin Department of Public Instruction to have taken the 4th-grade WKCE. Children were defined as either "exposed" (children tested at least once before their 3rd birthday with a result of ≥10 and <20 μg/dL, interpreted for study purposes as "moderately elevated BLL"), or "not exposed" (children tested between 18 and 36 months of age with a BLL of <5 μg/dL; interpreted for study purposes as "never exposed"). A child could only be classified as exposed if they never had a result 20 μg/dL or greater in their lifetime. Similarly, a child classified as not exposed could not have a BLL result of 5 μg/dL or higher at any age.

The BLL records of children in the WCLPPP database who met these definitions were matched with Department of Public Instruction records of 4th-grade WKCE completion. This match produced a list of 5779 children who had taken the WKCE, defined as exposed (3616) or unexposed (2163). Study staff provided this list of students (along with each student's date of birth and BLL information in a coded string indecipherable to non-study personnel) to an MPS data manager to obtain WKCE scores. For the 5779 eligible children, MPS was able to match 3757 in the district with 4th-grade WKCE scores. Those children for whom MPS was unable to find a match had most likely moved out of the district before the 4th grade. Figure 1 shows a flowchart of sample construction.

Student data and characteristics

The MPS returned a deidentified dataset to study researchers. The anonymized dataset of student records included WKCE scores, attendance and suspension data, and information on seven student characteristics including special education status, English Language Learner (ELL) status, race/ethnicity, gender, school attended, and year of birth. All students were listed with a single race/ethnicity status. Eligibility for free or reduced lunch during 4th grade was used as a marker for poverty, and was the only socioeconomic status variable available for analysis.

The leftmost columns in Table 1 show the distributions of student characteristics in our sample. Although recent research suggests important relationships between lead exposure and specific diagnoses associated with special education [24,25], our sample sizes for specific special education designations and uncertainty about the criteria used to determine them prevents reliable conclusions from being drawn. Students receiving any form of special education were therefore excluded from the regression analysis. Native American and Asian students were also excluded from further analysis owing to small sample sizes. Although only 7% of students in the overall sample were ELL, all but 4 of these students were identified as Hispanic. Among Hispanic students, the proportion of ELL was 38%.

Analysis

We used Chi-square tests of independence to investigate the bivariate relationship of each student characteristic with lead exposure. Effect sizes were calculated $\Phi = \sqrt{(\chi^2/N)}$. The Chi-square test for ELL and lead exposure considered Hispanic students only, to provide an unconfounded test of this important educational construct. The relationship between attendance rate and lead exposure was tested with a two-sample *t*-test, presented with effect size Cohen's *d*. Analyses were conducted using R version 2.12.2.

We conducted two sequential ordinary least-squares regressions for each of the five WKCE subject areas. The dependent variable for the initial models was student scaled score in that subject area. All covariates, but not lead exposure group, were included as predictor variables in the initial models: Male, assisted lunch eligibility, Black, Hispanic, ELL, suspension during the 4th grade, and attendance percentage. All predictor variables were binary coded, with the exception of attendance percentage, which was entered as a continuous variable.

Students' residual scores from the initial models were entered as the dependent variable for the secondary models. The only predictor in the secondary models was lead exposure. Exposure was coded as a binary variable (exposed/unexposed) because the size of our sample was insufficient to accurately test the specific dose-response of lead exposure for each academic subject at each level of BLL. This sequential regression analysis strategy removes all variance that can be attributed to covariates before looking for an effect of lead. Any effect found will provide evidence for the relationship between moderate lead exposure during child development and subsequent academic performance. A similar pair of multivariate regressions, testing the effects of covariates and exposure on the set of students' five WKCE scores was also conducted by approximating Pillai's trace to the F distribution.

Mean scores on the five WKCE subjects for students in the exposed and unexposed groups, adjusted to remove the effects of all covariates listed above, were obtained for graphical presentation using analysis of covariance.

Results

Sample representativeness

Table 1 evaluates sample representativeness by comparison to publicly available demographic data for all 4th- to 9th-grade students in MPS during 2008 and 2009 [26]. That cohort approximates the population from which our sample was drawn (4th graders from 2005 to 2010). A typical 9th-grade student in 2008 and 2009 would have taken the 4th-grade WKCE in 2004, only 1 year before the first WKCE scores in our sample. The demographic distributions in our sample approximate those present in the larger population.

Lead exposure associations with student characteristics

The distribution of student characteristics for the exposed and unexposed groups is shown in Table 2. In addition to the categorical associations in Table 2, students in the unexposed group had a higher mean attendance rate (95%) than students in the exposed group (92%), d = 0.40. All covariates were significantly associated with exposure at the $P < .0001$ level except for gender, which was significant at $P < .05$. Among the categorical covariates, race and poverty had the strongest relationships with lead exposure. Black/African-American students and Hispanic students were more likely to have been exposed to lead than White students, and students who were living in poverty were more likely to have been exposed than students who were not.

Effect of lead on WKCE scores

Models were fit for each of the five WKCE subject areas separately. Results of the initial models are shown in Table 3. Results of the secondary models are shown in Table 4. Beta coefficients in both models should be interpreted as the expected difference in test score owing to the presence of that characteristic. For example, based on Table 3, a male child would be expected to perform 4.51 points lower than a female child in language arts.

Children exposed to moderate amounts of lead performed significantly worse on all five sections of the WKCE compared with unexposed children ($P < .0001$ for each), even after removing all variance that could be explained by gender, poverty, racial/ethnic group, suspensions, and attendance. WKCE scale scores are not directly comparable across sections, however the effect of lead exposure was numerically greatest for the reading section, on which exposed students scored an average of 9.77 points lower than unexposed students (Table 4).

Adjusted mean scores for the exposed and unexposed groups are presented in Figure 2. The figure also shows the score cutoff thresholds for three of the four proficiency categories used by Wisconsin Department of Public Instruction: Basic, proficient, and advanced. The cutoff for minimal proficiency is below the plotted area and not shown. The graphs indicate that children in the exposed group are at greater risk of scoring in the basic range for language arts, mathematics, and reading. In the subject of science, a student scoring at the adjusted mean of the unexposed group would be classified as proficient, whereas a student scoring at the adjusted mean of the exposed group would be classified as basic. The disadvantage of an exposed student relative to an unexposed student can be contextualized as percentages of the intervals between the basic and proficient categories. Group differences in mean test score owing to moderate lead exposure range from 19% of the basic–proficient interval in science, to 42% of the basic–proficient interval in mathematics.

Discussion

The results of the current study show that a BLL of 10 to less than 20 μg/dL before age 3 years is associated with significantly lower standardized test scores in all five content areas of the 4th-grade WKCE after removing all variance attributable to gender, poverty, ELL status, race/ethnicity, suspension, and attendance percentage. The adjusted mean difference in scores for students in the exposed and unexposed groups was equivalent to 22% of the interval between categorization as "proficient" or "basic" in reading, and 42% of the interval in mathematics. Exposed students were more likely to score below the "proficient" level in both subjects, an outcome with negative consequences for both the individual students and their school.

These results punctuate the importance of environmental investigation and lead remediation for children with BLLs in this range. Wisconsin is not alone in having a standard for intervention that excludes some children with BLLs above the CDC reference level. Neighboring states Michigan and Iowa both use guidelines similar to Wisconsin's, and Minnesota requires investigation of BLLs at or above 15 μg/dL. Although data have consistently indicated that lead exposure in any amount is harmful, our study is one of only a few in the recent literature to quantify the relationship of moderate (often unremediated) lead exposure with classroom administered standardized test scores. Miranda et al [27] studied more than 8000 children in North Carolina, and revealed that performance on 4th-grade standardized tests of reading and math declined as BLL increased before 5 years of age. Miranda et al [28] concluded that lead exposure had the largest negative effect on school achievement test scores when combined with other risk factors (e.g., poverty, parental education level). The North Carolina researchers also found that increased BLLs were associated with an elevated risk of special education requirements [25]. Researchers in Detroit found robust associations of lead exposure and lower test scores in the 3rd, 5th, and 8th grades [29]. A study analyzing county-level data in New York State found the percentage of preschoolers with elevated BLL (>10 μg/dL) predicted 8% to 16% of the differences among counties in the percentage of their students scoring in the lowest category on 3rd- and 8th-grade English and mathematics tests [30]. Finally, an analysis of school-level data in Massachusetts found that schools experiencing the greatest reduction in mean student BLL from 2002 to 2009 also experienced the greatest increase in end-of-grade test scores over the same period, after controlling for covariates [31].

Although lead exposure has most typically been addressed as a public health or environmental issue, taken together these studies suggest that it should also be understood and studied as an educational issue with direct consequences for policy outcomes. Milwaukee is typical of many industrial Midwestern cities in the problems it faces controlling lead exposure in its large stock of older housing and contaminated soils. It is also typical of many urban areas in the complexity of issues faced by school districts, and pressures exerted on school districts to improve educational achievement. It is noteworthy that the racial/ethnic covariates account for considerably more variance in scores than does the lead exposure variable. That result is not an artifact of our particular statistical method, nor is it uncommon in the literature. There is, however, a crucial difference in how the variables in the model relate to phenomena in the world. Lead is a neurotoxin, and although more study is needed to fully understand the exact mechanisms by which it impairs cognitive function, several linking hypotheses have been put forward by researchers in the field, such as disrupted sensory gating mechanisms [32]. In contrast, the racial/ethnic covariates in our model are indirect markers for unmeasured characteristics of the children in our sample. The strong association between race/ethnicity and test scores inform us that a serious problem exists, but the covariates are frustratingly silent regarding the cause of the problem. Proposed approaches for reducing the racial achievement gap are numerous and often highly controversial. However, remediation strategies for lead exposure enjoy near consensus; funding must be provided to remove it from housing, the primary source of lead in children's environments [20,33,34]. The CDC Advisory Committee on Childhood Lead Poisoning Prevention makes the claim that “primary prevention is necessary because the effects of lead appear to be irreversible” [21], based on the finding that reducing BLLs in children postexposure using chelation therapy yields no benefit for cognitive outcomes [35]. Given the disproportionately high number of African-American and Hispanic students with elevated blood lead levels in our study, and the demonstrated negative relationship between lead exposure and standardized test scores, one strategy for reducing the racial achievement gap in schools would be to increase efforts to remove lead from housing.

We have been deliberately conservative in both our operationalization of ‘moderate’ lead exposure, and in the statistical methodology used to test its effect on end of grade test scores. The sequential regression analysis removed all variance that could be attributed to the covariates before testing for an effect of exposure, a method that was a priori biased against finding an effect of exposure. Additionally, the inclusion of suspension and attendance data as covariates likely further biased our test against finding an effect of exposure; research has suggested that both behavior problems and reduced immune system function may themselves be causally linked with lead exposure. Regardless, the effects are robust; performance was worse for children in the exposed group for each subject of the WKCE. The observed effects likely underestimate the magnitude of the true effects in the population. However, if we interpret our results as a lower bound on the true population effects, we may do so with greater confidence than if we had included all variables in a single model. They suggest a direct, quantifiable impact on educational outcomes that cannot be remediated through changes to school policy alone.

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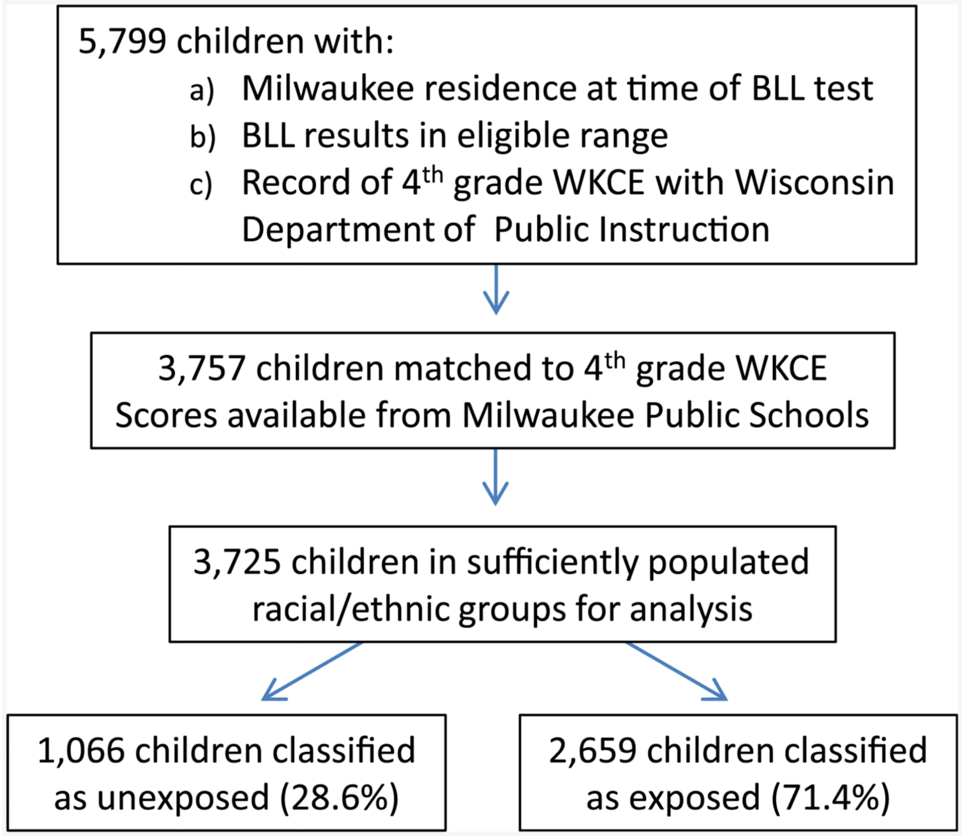

Fig. 1.
Participant flow diagram for Milwaukee Public Schools analysis.

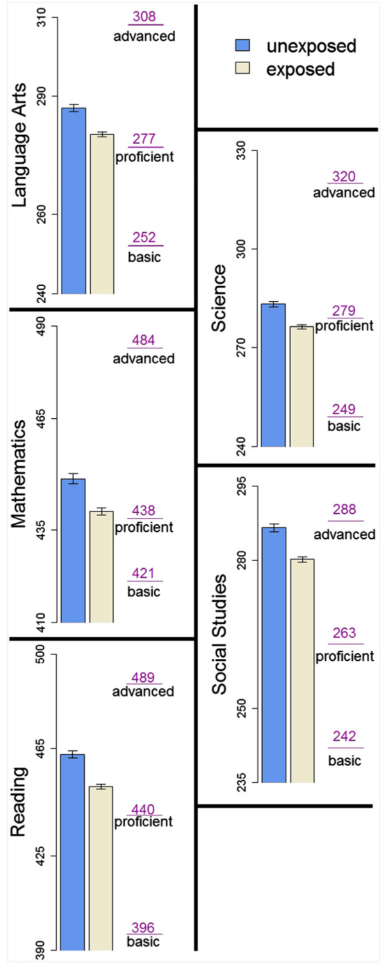

Fig. 2.

Adjusted mean scores and standard errors for exposed and unexposed students. Horizontal lines show cutoff thresholds for three of four proficiency categories used by the Wisconsin Department of Public Instruction.

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Table 1

Student characteristics and sample comparison

	WKCE sample		MPS 2008–2009 all 4th–9th graders	
	n	**%**	**n**	**%**
Total	3757	100	37,526	100
Lead exposure				
Exposed	2672	71	NA	NA
Unexposed	1085	29	NA	NA
Gender				
Male	1985	53	19,392	52
Female	1772	47	18,134	48
Race/ethnicity				
Asian	10	0	1674	5
Black/African-American	2489	66	21,631	60
Hispanic	775	21	8302	23
Native American	22	1	304	1
White	461	12	4409	12
Poverty indicator				
No assisted lunch	647	17	9132	24
Assisted lunch program	3110	83	28,394	76
Language indicator				
Native speaker	3509	93	33,746	90
English language learner	248	7	3780	10
Education designation				
Non-special education	2782	74	30,521	81
Special education	975	26	7365	19
Suspension incidents				
Suspended in 4th grade	957	25	NA	NA
Not suspended in 4th grade	2800	75	NA	NA

MPS = Milwaukee Public Schools; NA = not applicable; WKCE = Wisconsin Knowledge and Concepts Examination.

Table 2

Lead exposure covariates for WKCE sample

Characteristic	Unexposed		Exposed		Effect Size
	n	%	n	%	Φ
Total	1066	29	2659	71	
Gender *					.03
Male	534	27	1432	73	
Female	532	30	1227	70	
Race/ethnicity †					.31
Black/African-American	501	20	1988	80	
Hispanic	277	36	498	64	
White	288	62	173	38	
Poverty indicators †					.31
No assisted lunch	336	64	193	36	
Assisted lunch program	730	23	2466	77	
Language † (Hispanic students only)					.17
Native speaker	203	42	277	58	
English language learner	74	25	221	75	
Education designation †					.12
Non-special education	877	32	1879	68	
Special education	187	19	780	81	
Suspension incidents †					.21
Suspended in 4th grade	114	12	834	88	
Not suspended in 4th grade	952	34	1825	66	

* $P < .05$ for Chi-square test of independence.

† $P < .0001$ for Chi-square test of independence.

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Table 3

Effect of covariates on WKCE scores (model 1)

Predictor	Language arts		Mathematics		Reading		Science		Social studies		Multivariate	
	Beta	P	Beta	P	Beta	P	Beta	P	Beta	P	Pillai	P
Intercept	245.70	***	368.04	***	426.09	***	251.44	***	263.47	***	–	–
Male	−4.51	***	7.87	***	−1.24	.41	2.47	.02	0.13	.89	0.0379	***
Assisted lunch	−8.80	***	−10.79	***	−16.52	***	−10.15	***	−11.56	***	0.0291	***
ELL	−13.24	***	−11.88	**	−22.44	***	−7.22	*	−7.20	**	0.0227	***
Black/African American	−15.41	***	−27.78	***	−25.69	***	−20.28	***	−16.12	***	0.0598	***
Hispanic	−5.95	*	−10.84	**	−13.63	***	−8.68	***	−7.15	**	0.0092	**
Suspension	−5.35	**	−6.55	*	−7.26	***	−4.90	**	−4.38	**	0.0070	*
Attendance %	0.64	***	1.10	***	0.71	***	0.55	***	0.45	***	0.0293	***
F(7, 2748)	56.27		66.61		65.92		72.60		68.09		–	–
Adjusted R^2	0.1236		0.1430		0.1418		0.1545		0.1461		–	–

ELL = English language learner.

* $P < .01$;

** $P < .001$;

*** $P < .0001$.

Table 4

Unique effect of lead exposure on WKCE scores (model 2)

Predictor	Language arts		Mathematics		Reading		Science		Social studies		Multivariate	
	Beta	***P***	**Beta**	***P***	**Beta**	***P***	**Beta**	***P***	**Beta**	***P***	**Pillai**	***P***
Intercept	3.71	**	4.86	**	6.66	***	3.80	***	3.55	***		
Lead exposure	−5.44	***	−7.14	***	−9.77	***	−5.58	***	−5.21	***	0.0149	***
F(1, 2754)	22.84		18.80		38.62		27.01		28.48		–	–
Adjusted R^2	0.0079		0.0064		0.0135		0.0094		0.0099		–	–

* $P < .01$;

** $P < .001$;

*** $P < .0001$.