HHS Public Access
Author manuscript
Soc Sci Med. Author manuscript; available in PMC 2016 May 01.

Published in final edited form as:
Soc Sci Med. 2015 May ; 132: 122–131. doi:10.1016/j.socscimed.2015.03.032.

Does neighborhood deprivation modify the effect of preterm birth on children's first grade academic performance?

Jennifer L. Richards[a], **Theresa Chapple-McGruder**[b], **Bryan L. Williams**[a,c], and **Michael R. Kramer**[a]

Jennifer L. Richards: jennifer.richards@emory.edu; Theresa Chapple-McGruder: theresa.chapple-mcgruder@dph.ga.gov; Bryan L. Williams: bryan.williams@emory.edu; Michael R. Kramer: mkram02@emory.edu

[a]Department of Epidemiology, Rollins School of Public Health, Emory University, 1518 Clifton Road, NE, Atlanta, GA 30322

[b]Office of Epidemiology, Maternal and Child Health Program, Georgia State Department of Health, 2, Peachtree Street NW, Atlanta, GA 30303

[c]Nell Hodgson Woodruff School of Nursing, Emory University, 1520 Clifton Road NE, Atlanta, GA, 30322-4027

Abstract

Children's cognitive development and academic performance are linked to both fetal and early childhood factors, including preterm birth and family socioeconomic status. We evaluated whether the relationship between preterm birth (PTB) and first grade standardized test performance among Georgia public school students was modified by neighborhood deprivation in early childhood.

The Georgia Birth to School cohort followed 327,698 children born in Georgia from 1998–2002 through to end-of-year first grade standardized tests. Binomial and log-binomial generalized estimating equations were used to estimate risk differences and risk ratios for the associations of both PTB and the Neighborhood Deprivation Index for the census tract in which each child's mother resided at the time of birth with test failure (versus passing). The presence of additive and multiplicative interaction was assessed.

PTB was strongly associated with test failure, with increasing risk for earlier gestational ages. There was positive additive interaction between PTB and neighborhood deprivation. The main effect of PTB versus term birth increased risk of mathematics failure: 15.9% (95%CI: 13.3–18.5%) for early, 5.0% (95% CI: 4.1–5.9%) for moderate, and 1.3% (95%CI: 0.9–1.7%) for late preterm. Each 1 standard deviation increase in neighborhood deprivation was associated with 0.6% increased risk of mathematics failure. For children exposed to both PTB and higher neighborhood deprivation, test failure was 4.8%, 1.5%, and 0.8% greater than the sum of two main

Corresponding Author: Michael R. Kramer, MS MMSc PhD, Department of Epidemiology, Rollins School of Public Health, Emory University, 1518 Clifton Road, Room 3043, Atlanta, GA 30322, mkram02@emory.edu, (404) 727-9818.

effects for early, moderate, and late PTB, respectively. Results were similar, but slightly attenuated, for reading and English/language arts.

Our results suggest that PTB and neighborhood deprivation additively interact to produce greater risk among doubly exposed children than would be predicted from the sum of the effects of the two exposures. Understanding socioeconomic disparities in the effect of PTB on academic outcomes at school entry is important for targeting of early childhood interventions.

Keywords

Preterm birth; Neighborhood deprivation; Socioeconomic status; Academic achievement; Interaction

INTRODUCTION

Children's cognitive development and academic performance are linked to both fetal and early childhood factors, including being born preterm (<37 weeks gestation) and growing up in a family with lower socioeconomic status (SES) [Figure 1] (Allen, 2008; Aylward, 2005; Brooks-Gunn & Duncan, 1997). Children who are born preterm are at higher risk of severe neurologic impairments (e.g., cerebral palsy, blindness, deafness) as well as more subtle motor and neurocognitive deficits (e.g., cognitive ability, motor skills, visual-motor skills, language, executive function, behavior, academic achievement) (Allen, 2008; Aylward, 2005; Ferrari et al., 2012; McGowan et al., 2011; Pugliese et al., 2013). Improving survival rates among very and moderately preterm infants has resulted in increased prevalence of these less severe deficits (Allen, 2008). Children who are raised in poverty are more likely to experience developmental delays and learning disabilities; to display worse verbal ability and achieve lower scores on intelligence and achievement tests; and to have lower academic achievement (e.g., high school completion, grade repetition) (Brooks-Gunn & Duncan, 1997). Hypothesized pathways through which childhood poverty may result in poorer cognitive and academic outcomes include the home environment (e.g., opportunities for learning, reading materials), parents' interactions with their children, parental mental health (e.g., irritability, depression), and neighborhood conditions (e.g., resources for child development such as playgrounds, parks, quality preschool, after-school programs) (Brooks-Gunn & Duncan, 1997).

Studies of the neurocognitive consequences of preterm birth often treat individual- and/or neighborhood-level SES (e.g., maternal education, family income, neighborhood poverty) as confounders to control. However, SES may modify (e.g. interact with) the effect of preterm birth on cognitive development. For instance, children who are born preterm may be particularly susceptible to the effects of family and social environments, in terms of providing emotional and material resources and social experiences that are critical for academic success at school age (Brooks-Gunn & Duncan, 1997; Christensen et al., 2014; Guo & Harris, 2000).

In the United States in particular, some children may be more likely to have been born preterm and into a lower SES environment, experiencing 'double jeopardy'. It has been observed that racial and social class disparities in academic readiness parallel disparities in preterm birth rates as well as individual- and neighborhood-level SES (Culhane & Goldenberg, 2011; Lee & Burkam, 2002). Fundamental processes of social stratification – including residential segregation into certain neighborhoods, as well as the accumulation and transfer of wealth and resources over individuals' lives and across generations – may contribute to both risk of preterm birth and to the resources available to children's families. All of this raises questions as to the effects of being doubly exposed to both preterm birth and lower SES (both at the individual level and in terms of the neighborhoods in which children are raised) on children's academic readiness (Acevedo-Garcia et al. 2008; Collins et al., 2011; Kramer et al., 2010; Weisglas-Kuperus et al., 1993). The causal notion of effect measure modification or heterogeneity is typically operationalized in statistical models with interaction terms. Additive interaction means that the effect of being doubly exposed is greater or less than the sum of the effects of the two main exposures, whereas multiplicative interaction suggests that the observed effect of being doubly exposed departs from the product of the effect of the two exposures (VanderWeele & Knol, 2014). Considering additive interaction, imagine that preterm birth (versus term) and being raised in a low SES family (versus a high SES family) independently increase a child's risk of developmental delay by 10% and 20%, respectively. In the absence of effect modification, a doubly exposed child would experience 30% increased risk (or the sum of the individual effects). If there were positive additive interaction, the combined effect would be greater than 30%; conversely if there were negative additive interaction, the combined effect would be less than 30%. Studies in Taiwan and Sweden reported that the effect of preterm birth on school tests scores at age 15–16 varied across strata of parental education. The Taiwanese study used linear regression and thus detected the interaction on the additive scale whereas the Swedish study used logistic regression, detecting multiplicative interaction. In these and other studies, operationalization of the causal notion of effect measure modification is often dictated by the statistical model chosen rather than by a conceptual framework. It has been argued that additive interaction is the form of heterogeneity of greatest interest in public health (Rothman et al., 2012).

Extant research provides some evidence of interaction between birth outcome and individual SES on child development, but less work has evaluated area-based SES as an effect modifier. Preterm birth rates (Messer et al., 2008) and children's academic performance (Bradley & Corwyn, 2002; Sampson et al., 2008; Sastry & Pebley, 2010) are each affected by area- or neighborhood-level deprivation or disadvantage. In a small study of extremely low birth weight (ELBW) children born in 1992–1995 in a single tertiary care facility, Andreias et al. (2010) found that both individual- and neighborhood-level SES were associated with academic achievement test performance at age 8 years, with no evidence of interaction. Further investigation is required with population-based samples using the full distribution of prematurity. We know of no studies that have investigated whether the relationship between preterm birth and academic outcomes is modified by children's exposure to neighborhood-level SES during their early childhood years.

In this study we aim to assess modification of the effect of preterm birth on first grade academic performance by neighborhood SES, controlling for individual-level SES using a retrospective, population-based cohort of children born in the state of Georgia from 1998–

2002. We hypothesized supra-additive interaction between preterm birth and neighborhood deprivation such that children born at earlier gestational ages in more deprived neighborhoods would have poorer school readiness than those born in less deprived neighborhoods.

METHODS

The Georgia Birth to School retrospective cohort consists of singleton live births to Georgia-resident mothers. Construction of this cohort has been previously described (Feng et al., 2013; Williams et al., 2013), but in brief birth certificates from 1998–2002 were linked to their Georgia public school first grade Criterion-Referenced Competency Test (CRCT) scores from 2005 to 2009. Children were included if they were 6 to 8 years old when they took the first grade CRCT; had a gestational age of 20–43 weeks and birth weight of 400–5000 grams; and if they were born to non-Hispanic white, non-Hispanic black, or Hispanic mothers. Based on these criteria, there were 334,350 children eligible for analyses. Children were excluded if they could not be linked to a census tract (n=1,337), were born in a census tract lacking data on neighborhood-level variables for the year 2000 (n=32), had an outlier value for neighborhood deprivation as described below (n=2,172), or were born in a census tract with fewer than 50 births during the study period (n=3,111). Exclusions varied only slightly by maternal race/ethnicity; 1.5% of children of non-Hispanic white mothers, 3.2% of children of non-Hispanic black mothers, and 0.6% of children of Hispanic mothers were excluded.

Gestational age

Gestational age was measured as weeks from mother's last menstrual period, as reported on the birth certificate. Gestational age category was defined as early preterm (<28 weeks), moderate preterm (28–33 weeks), late preterm (34–36 weeks) versus term (≥37 weeks). We considered sub-classifying term births into early term (37–38 weeks), term (39–41 weeks), and post term (≥42 weeks), based on recent work on variation in risk of adverse neonatal outcomes across the gestational spectrum ("ACOG Committee Opinion No 579," 2013). However, we found the early term and post term categories were not meaningfully different from the term category. Therefore, for our final analyses, we collapsed these categories into a single term category that served as the referent group.

Early childhood contextual environment

Children's exposure to area-based deprivation during their early childhood years was measured using the previously validated Neighborhood Deprivation Index (NDI) for the census tracts in which their mothers resided at birth (Messer et al., 2006, 2008; O'Campo et al., 2008). Tract-specific NDI scores were computed using Census 2000 data and were a function of poverty rates, household income, receipt of public assistance, occupation, housing overcrowding, education, and employment. NDI was standardized, and our analytic sample was restricted to children with NDI values within 3 SD of the mean in order to exclude outlier exposure values. Individual-level indicators of SES included maternal education and whether Medicaid was the payor for delivery (a proxy for maternal income).

First grade CRCT performance

The Georgia Department of Education implements the CRCT to assess academic performance on specific state-designated competencies in mathematics, reading, and English/language arts. Students can exceed, meet, or not meet state standards in each content area. During the study period, CRCT examinations were administered to first graders each spring ("Criterion-Referenced Competency Tests (CRCT)"). Our main analyses focus on failing (i.e., not meeting the standard) the first grade CRCT examination in mathematics, given evidence that preterm children may have particular difficulty in mathematics (Simms et al., 2013). We also analyzed children's performance in reading and English/language arts. These results were similar, and are presented in the web supplement.

Covariates

The following variables were identified from birth certificate records and considered as potential confounders: maternal age at birth (15–17 years, 18–19 years, 20–24 years, 25–29 years, 30–34 years, 35–39 years, 40 years and older), maternal race/ethnicity (non-Hispanic white, non-Hispanic black, Hispanic), whether Medicaid was the payor for delivery, maternal smoking during pregnancy, child's sex, and child's age at taking the first grade CRCT (computed assuming the CRCT date for each calendar year was April 15). Maternal education at the time of birth (less than high school, completed high school, up to 3 years postsecondary, 4 or more years postsecondary) was considered either as a confounder or as a mediator, as discussed below.

Statistical analyses

To describe the observed joint distribution of preterm birth and neighborhood deprivation, we report proportions of children failing each of the CRCT assessments for our study population stratified into 16 sub-groups of 4 gestational age categories and 4 NDI quartiles.

Multivariable analysis with generalized estimating equations (GEE) based on binomial and log-binomial distributions estimate risk differences (RD) and risk ratios (RR) respectively, and accounted for clustering by census tract. Subjects with missing data on any covariate or the outcome were excluded from adjusted analyses. First, we considered main effects models to determine the mutually adjusted independent associations of preterm birth and NDI with CRCT test failure. Second, we assessed additive and multiplicative interaction between preterm birth and NDI by including interaction terms in GEE models based on the binomial and log-binomial distributions, respectively. For each model, the set of three interaction terms between gestational age category and NDI (i.e., early preterm × NDI, moderate preterm × NDI, late preterm × NDI) were assessed for statistical significance using the generalized score test statistic. We further evaluated additive interaction with the relative excess risk due to interaction (RERI) from the relative risk model (see formula in Web Supplement) (VanderWeele & Knol, 2014). $RERI_{RR} > 0$ indicates the presence of positive additive interaction, whereas $RERI_{RR} < 0$ corresponds to negative additive interaction; however, these measures cannot be used to determine the magnitude of interaction.

Maternal education could conceivably be a confounder of the association if maternal education is a cause or correlate of a cause for preterm birth (El-Sayed & Galea, 2012;

Goldenberg et al. 2008) or NDI (Kerckhoff et al, 2001), and also a determinant of child's inherited abilities and pre-school support for education (Deary & Johnson, 2010). On the other hand, attained maternal education might be a consequence of the school quality and socioeconomic environment of the mother (Deary & Johnson, 2010), and to the extent that maternal pre-conceptional SES is correlated with pregnancy SES, maternal education might mediate the effect of neighborhood SES on academic performance. Thus, we considered models that control for maternal education as a confounder, and models that estimate the total effect of neighborhood SES on child academic performance without control for maternal education.

Missing data and sensitivity analyses

A total of 6,340 (1.9%) of subjects were missing data on at least one covariate; 4,810 (1.5%) were missing maternal education, 18 (0.01%) were missing marital status, and 1695 (0.5%) were missing smoking. There were no meaningful differences in missing data by preterm birth category or by maternal race/ethnicity with the exception of Hispanic children being more likely to be missing maternal education data (7.1%, versus 0.8% of non-Hispanic white children and 1.0% of non-Hispanic black children). Few subjects were missing outcome data, and there were no meaningful differences in missingness by preterm birth category, maternal education, or maternal race/ethnicity. CRCT mathematics was missing for 382 (0.1%), CRCT reading for 318 (0.1%), and CRCT English/language arts for 357 (0.1%). Only 89 (0.03%) subjects were missing scores for all three tests.

Sensitivity analyses assessed the impact of missingness by multiply imputing missing values, as well as the impact of excluding subjects in census tracts with fewer than 50 births.

Descriptive and regression analyses were conducted using SAS 9.4 (Carey, NC), and bootstrapping of RERI confidence intervals was conducted using R 3.1 (R Foundation for Statistical Computing, Vienna Austria). The parent project was reviewed and approved by the Emory University Institutional Review Board.

RESULTS

There were 327,698 subjects eligible for inclusion in our study cohort, of whom 12.7% (41,657) failed the CRCT mathematics examination. Overall, 10.2% (33,287) of children in our study population were born preterm, including 0.3% (1,127) early preterm, 1.9% (6,276) moderate preterm, and 7.9% (25,884) late preterm. The mean standardized NDI was −0.09 (SD 0.90) across all infants, who were born in 1,501 census tracts. Table 1 presents characteristics of children in the cohort. About 55% of infants were born to non-Hispanic white mothers, 36% to non-Hispanic black mothers, and 10% to Hispanic mothers. One-quarter of mothers did not complete high school, 38% were unmarried, 47% had Medicaid as the payor for delivery, and 9% reported smoking during pregnancy.

Table 2 reports observed proportions of CRCT mathematics failure stratified by gestational age and NDI quartiles. Earlier gestational age and worsening neighborhood deprivation both resulted in increasing risk of CRCT mathematics failure. Unadjusted additive and multiplicative interaction can be examined from these data. Among term-born children, those born in the most deprived quartile had 11.9% or 2.9 times increased risk of CRCT failure compared to those born in the least deprived quartile. Among children born in the least deprived quartile, those born early preterm had 11.5% or 2.8 times increased risk of CRCT failure compared to those born at term. Therefore, the expected joint effect comparing the highest risk category (early preterm, most deprived quartile) to the lowest risk category (term, least deprived quartile) would be 23.3% or 8.0 times increased risk of CRT failure. The observed RD (32.3%) and observed RR (6.1) suggested the presence of positive additive interaction and negative multiplicative interaction.

In unadjusted main effects models (Table 3), preterm birth and NDI were each significantly associated with increased risk of CRCT mathematics failure. Mathematics failure was significantly higher among all preterm children, with an increasing trend in risk for earlier births ($p<0.0001$). Each 1 standard deviation (SD) increase in NDI was associated with a 5.5% (95% CI: 5.3, 5.8) increase in absolute risk and 43% (95% CI: 40, 46) increase in relative risk of failing CRCT mathematics. Of note, we also observed substantial disparities in CRCT performance by maternal race/ethnicity and maternal education. Children born to non-Hispanic black and Hispanic mothers and to mothers with lower education experienced higher prevalence of CRCT mathematics failure.

Preterm birth and NDI remained as significant independent correlates of CRCT performance in adjusted main effects models [Table 3, Models I and II]. The estimated effects of early, moderate, and late preterm birth were slightly attenuated compared to crude models, regardless of whether maternal education was controlled as a confounder. Estimated risk of CRCT failure was highest for children born early preterm: there was an approximate doubling of risk – corresponding to a 16.8% increase in absolute risk – for these children compared to their peers born at term. The estimated effect of NDI was substantially attenuated in adjusted models, and varied between models that did or did not adjust for maternal education. In the adjusted model treating maternal education as a confounder to be controlled, each 1 SD increase in NDI was associated with 0.6% increased absolute risk and 3% increased relative risk of CRCT failure, whereas adjusted models not controlling for maternal education suggested a 1.7% increased absolute risk and 11% increase in relative risk of CRCT failure. Maternal race/ethnicity and maternal education remained important predictors of CRCT mathematics failure in the fully adjusted model, although their effects were slightly attenuated after adjustment for covariates.

Interaction models suggested the presence of positive additive interaction but negative multiplicative interaction between preterm birth and NDI in their effects on CRCT mathematics failure [Table 4]. In additive models, preterm birth and increasing NDI were independently associated with higher risk of CRCT failure, and the effect of experiencing both exposures was larger than the sum of their independent effects. Estimated RDs for the effect of preterm birth increased in magnitude as NDI increased. In the fully adjusted additive model, for example, the RD for early preterm versus term birth was 11.1% (95% CI: 7.5, 14.7) at a low deprivation score (NDI = −1) versus 20.6% (95% CI: 16.9, 24.3) at a high deprivation score (NDI = 1). Removing maternal education did not substantially affect regression estimates, but did result in a slightly increased RD for NDI (change from 0.6% to 1.7% increased risk for each 1 SD increase).

In contrast to the results on the additive scale, multiplicative models suggested that the joint estimated effect of preterm birth and NDI on CRCT mathematics failure was less than the product of their independent effects [Table 4]. In the fully adjusted multiplicative model, for example, the RR for early preterm birth was 2.36 (95% CI: 2.03, 2.75) at a low deprivation score (NDI = −1), but was 1.99 (95% CI: 1.81, 2.19) at a high deprivation score (NDI = 1). RERI calculations for interaction of early preterm, moderate preterm, and late preterm birth with NDI using adjusted RRs from multiplicative models were null with point estimates <0 [Table 4].

In sensitivity analyses, our results were unchanged after including subjects born in census tracts with fewer than 50 births during the study period, and after multiply imputing observations with missing covariate values. Descriptive and model results for the alternate outcomes CRCT reading and English Language Arts were qualitatively consistent with those reported above for mathematics (web supplement).

DISCUSSION

School entry is a critical transition point in children's lives that sets the stage for future social and academic achievement and potentially influences life course socioeconomic and health trajectories (Conti & Heckman, 2010; Heckman, 2006). Understanding social and biological factors affecting early academic performance at this age is important for addressing achievement disparities (Lee & Burkam, 2002; Alexander et al., 1993). We hypothesized that children doubly exposed to both the fetal insult of preterm birth and the early childhood insult of high neighborhood deprivation would experience a supra-additive 'double jeopardy' effect, producing even worse academic performance at the beginning of primary schooling than the simple additive effects of the two individual exposures.

We found that preterm birth was a clear predictor of early school performance in mathematics, reading, and English Language Arts. Children born the earliest were most profoundly impacted, experiencing more than a doubling of risk compared to their term-born peers. Neighborhood deprivation index (NDI) was a moderate predictor of CRCT failure in unadjusted analyses, but its effect was substantially attenuated after controlling for covariates, particularly correlates of individual SES (e.g. maternal education). There was evidence of a supra-additive interactive effect between preterm birth and NDI in additive interaction analyses. For mathematics analyses, experiencing both exposures resulted in an additional increased absolute risk of 4.8%, 1.5%, and 0.8% for early preterm, moderate preterm, and late preterm children, respectively, for each 1 SD increase in NDI. In contrast we found that there was negative multiplicative interaction between the two exposures, which by itself is not an uncommon phenomenon to find in tandem with positive additive interaction (VanderWeele & Knol, 2014). However, in our assessment of additive interaction using RRs from log-binomial models, we found negative (albeit statistically null) values for RERI which do not agree with our assessment of additive interaction from binomial models. While there has been at least one published review of sample size and power calculations for detecting additive interactions on the risk scale and using RERI (Vanderweele, 2012), similar techniques are not yet available for the case of considering additive interaction between categorical and continuous exposures. It is possible that both of our results are consistent with there being no additive interaction between preterm birth and NDI (e.g., small effect size of additive interaction observed in binomial-identity models), or that our RERI calculations lack the statistical power to detect small additive interaction effect sizes. This issue requires further study by statistical methodologists.

Our findings add to existing knowledge regarding the contributions of fetal and early childhood factors to long-term neurodevelopmental and academic outcomes in children. Prior studies of interaction between individual-level SES and preterm birth have yielded mixed findings, perhaps in part due to evaluating different types of interaction (i.e., additive or multiplicative). Using linear regression to assess additive interaction, Wang et al. (2008) found that deficits in Mandarin test scores between Taiwanese children born preterm, at low birth weight, or both were smaller among those whose fathers completed more years of education; however, there was no meaningful difference in the effect across educational levels for mathematics and science tests. Gisselmann et al. (2010) used logistic regression to assess multiplicative interaction, and similarly found that preterm birth was associated with worse scores in Swedish language only among Swedish children whose parents both had less than 3 years of secondary education. Another recent study assessed multiplicative interaction between family SES and moderate preterm birth (32–35 weeks) in their effects on developmental delay at 4 years among children enrolled in the Longitudinal Preterm Outcome Project in the Netherlands. The authors found negative multiplicative interaction between lower SES and moderate preterm birth for delay in communication skills, but no significant interaction for other developmental delay outcomes (Potijk et al., 2013)

We hypothesized a synergistic effect between preterm birth and neighborhood deprivation in their effects on academic performance, and found some evidence of positive additive interaction. However, others have argued that social factors (e.g., individual-level SES) and biological factors (e.g., preterm birth) may compete in their effects on childhood outcomes. A review by Hack et al. (1995) noted that while it has been hypothesized that these factors act synergistically, some evidence suggests that differences in long-term outcomes between low birth weight and normal birth weight children were greater in more advantaged environments compared to less advantaged environments. The authors suggested that the added insult of being born at low birth weight did not contribute substantial additional risk of long-term poor outcomes on top of being born in a more disadvantaged environment (Hack et al., 1995). Similar ideas relating to children’s IQ were explored by Turkheimer et al. (2003), finding that IQ in higher SES children may be driven less by environment and more by genetics, with the opposite being true in lower SES children. Using data from twins enrolled in the National Collaborative Perinatal Project, the authors modeled variation in IQ as a function of genotype, shared environment, and nonshared environment, each of which was allowed to interact with SES (Turkheimer et al., 2003). Further studies are needed to explore these competing hypotheses about interaction between preterm birth and SES or other aspects of early life environment in their effects on children’s neurodevelopment and academic outcomes, with particular emphasis on additive rather than multiplicative interaction as the more plausible scale for causal interaction (Rothman et al., 2012; VanderWeele & Knol, 2014).

This study has several important strengths. The Georgia Birth to School retrospective cohort is a large, population-based study covering all live births in Georgia that could be linked to CRCT scores in public school records. NDI is a validated measure representing multiple domains of neighborhood deprivation (e.g., poverty, employment, education), which has been used in studies of neighborhood-level effects on perinatal outcomes (Messer et al., 2006, 2008; O'Campo et al., 2008). By combining both area-based NDI and proxies of individual SES (maternal education and Medicaid status), this contributes to prior studies solely restricted to consideration of individual SES.

However, there are also limitations to our study. First, birth census tract may be an imperfect proxy for children's early life environment because of residential mobility. We may have misclassified children if they moved to a neighborhood characterized by better or worse deprivation during early childhood. Further, the timing and persistence of exposure to poverty and deprivation over early childhood may affect its impact on academic outcomes. Childhood poverty may have a more profound effect on children's cognitive ability and academic performance when experienced early and/or persistently during childhood (Brooks-Gunn & Duncan, 1997; Dickerson & Popli, 2011; Duncan et al., 1998; Guo, 1998). While we did not have data on subsequent residences after birth, we were able to identify the census tract in which each child attended school for 97% (n=318,019) of subjects. Recognizing that this may only be an approximation of each child's exposure to area-level deprivation at first grade (e.g., they may have attended school in a different census tract from where they actually resided), and whether they moved between birth and attending school, we calculated the difference in NDI between birth and school measurements. The mean difference in NDI was −0.13 (SD = 0.80, quartile 1 = −0.49, quartile 3 = 0.20), suggesting that there was not substantial change between birth and school, although pointing in the direction of more children being born in a more deprived neighborhood and attending school in a slightly less deprived neighborhood. Second, our analyses may also be affected by uncontrolled structural confounding of the effect of NDI on academic outcomes due to social stratification in our study population, leading lower SES individuals and minority racial/ethnic groups to be concentrated in certain areas (Messer et al., 2010). Especially in urban areas of Georgia, economic and social deprivation is patterned along racial lines, with minority populations often concentrated in high deprivation areas. Structural confounding may be present when selection factors into the exposed and unexposed groups make it unlikely that each group would ever experience the implied counterfactual exposure condition. Third, a small proportion of subjects were excluded from analyses due to missing data on covariates and outcomes. Missing outcome data did not vary meaningfully by subject characteristics, and analyses using multiple imputation of missing covariate data did not change our findings.

There is a growing body of literature that suggests that school quality and positive school climates (i.e., intangible and unique characteristics of a school that influence student attitudes and values) can mitigate the effects of poverty on educational achievement (Hopson & Lee, 2011; Komro et al., 2011; National Center for Education Statistics, 2000). While the mediating roles of school quality and climate should be investigated, our focus on early academic outcomes in first grade focuses attention on the pre-school determinants of academic achievement, assuming a relatively lower role of school quality at this early point in children's school careers.

The Georgia CRCT is an early indicator of academic achievement, but it is not a direct test of children's cognitive ability or intelligence. The CRCT is a criterion-referenced test that measures students' attainment of specific knowledge and skills according to established criteria set by the Georgia DOE. The CRCT is scaled to distinguish children who fail to meet, meet, or exceed standards, and as such more nuanced patterns are not possible. The body of literature on preterm birth and neurodevelopment shows that being born earlier is associated with a breadth of deficits in specific areas (e.g., language, motor, visual-sensory) as well as academic performance, and future analyses of interaction between preterm birth and SES should consider more specific neurodevelopmental and academic outcomes.

In conclusion, our findings suggest that preterm birth and neighborhood deprivation each independently increase children's risk of poorer academic performance at school entry. The two factors additively interact to produce even greater risk among doubly exposed children than would be predicted from the sum of the effects of the two exposures. Further research is needed to elucidate interactions between neighborhood deprivation and birth outcomes in additional populations, considering various measures of children's early life environment as well as their cognitive and academic outcomes, and to investigate potential mediating factors such as home environments, parenting characteristics, and school quality and climates.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Ms. Richards received support from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) of the National Institutes of Health (NIH) T32 Predoctoral Training Program in Reproductive, Perinatal, and Pediatric Epidemiology under Award Number T32HD052460. Dr. Kramer received support from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD) of the National Institutes of Health (NIH) under Award Number K01HD074726. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The authors wish to acknowledge the support and contribution of the Office of Health Indicators for Planning and the Maternal and Child Health Program, both of the Georgia Department of Public Health for their assistance in providing the linked data.

References

Acevedo-Garcia D, Osypuk TL, McArdle N, Williams DR. Toward a policy-relevant analysis of geographic and racial/ethnic disparities in child health. Health Affairs (Project Hope). 2008; 27(2): 321–333. [PubMed: 18332486]

ACOG Committee Opinion No 579: Definition of term pregnancy. Obstetrics and Gynecology. 2013; 122(5):1139–1140. [PubMed: 24150030]

Alexander KL, Entwisle DR, Dauber SL. First-grade classroom behavior: Its short- and long-term consequences for school performance. Child Development. 1993; 64(3):801. [PubMed: 8339696]

Allen MC. Neurodevelopmental outcomes of preterm infants. Current Opinion in Neurology. 2008; 21(2):123–128. [PubMed: 18317268]

Aylward GP. Neurodevelopmental outcomes of infants born prematurely. Journal of Developmental and Behavioral Pediatrics: JDBP. 2005; 26(6):427–440. [PubMed: 16344661]

Bradley RH, Corwyn RF. Socioeconomic status and child development. Annual Review of Psychology. 2002; 53:371–399.

Brooks-Gunn J, Duncan GJ. The effects of poverty on children. The Future of Children. 1997; 7(2): 55–71. [PubMed: 9299837]

Christensen DL, Schieve LA, Devine O, Drews-Botsch C. Socioeconomic status, child enrichment factors, and cognitive performance among preschool-age children: results from the Follow-Up of Growth and Development Experiences study. Research in Developmental Disabilities. 2014; 35(7): 1789–1801. [PubMed: 24679548]

Collins JW, Rankin KM, David RJ. African American women's lifetime upward economic mobility and preterm birth: the effect of fetal programming. American Journal of Public Health. 2011; 101(4):714–719. [PubMed: 21330589]

Conti G, Heckman JJ. Understanding the Early Origins of the Education-Health Gradient: A Framework That Can Also Be Applied to Analyze Gene-Environment Interactions. Perspectives on Psychological Science : A Journal of the Association for Psychological Science. 2010; 5(5): 585–605. [PubMed: 21738556]

Criterion-Referenced Competency Tests (CRCT). (n.d.). Retrieved August 15, 2014, from https://www.gadoe.org/Curriculum-Instruction-and-Assessment/Assessment/Pages/CRCT.aspx

Culhane JF, Goldenberg RL. Racial disparities in preterm birth. Seminars in Perinatology. 2011; 35(4): 234–239. [PubMed: 21798403]

Deary IJ, Johnson W. Intelligence and education: causal perceptions drive analytic processes and therefore conclusions. International Journal of Epidemiology. 2010; 39(5):1362–1369. [PubMed: 20504860]

Dickerson, A.; Popli, G. Persistent poverty and children's cognitive development: evidence from the UK Millennium Cohort Study (Working Paper No. 2011023). The University of Sheffield, Department of Economics; 2011. Retrieved from http://ideas.repec.org/p/shf/wpaper/2011023.html

Duncan GJ, Yeung WJ, Brooks-Gunn J, Smith JR. How much does childhood poverty affect the life chances of children? American Sociological Review. 1998; 63(3):406.

El-Sayed AM, Galea S. Temporal changes in socioeconomic influences on health: maternal education and preterm birth. American Journal of Public Health. 2012; 102(9):1715–1721. [PubMed: 22742063]

Feng J, Kramer MR, Dever BV, Dunlop AL, Williams B, Jain L. Maternal smoking during pregnancy and failure of the Georgia first grade criterion-referenced competency test. Paediatric and Perinatal Epidemiology. 2013; 27(3):275–282. [PubMed: 23574416]

Ferrari F, Gallo C, Pugliese M, Guidotti I, Gavioli S, Coccolini E, Bertoncelli N. Preterm birth and developmental problems in the preschool age. Part I: minor motor problems. The Journal of Maternal-Fetal & Neonatal Medicine: The Official Journal of the European Association of Perinatal Medicine, the Federation of Asia and Oceania Perinatal Societies, the International Society of Perinatal Obstetricians. 2012; 25(11):2154–2159.

Goldenberg RL, Culhane JF, Iams JD, Romero R. Epidemiology and causes of preterm birth. The Lancet. 2008; 371(9606):75–84.

Guo G. The timing of the influences of cumulative poverty on children's cognitive ability and achievement. Social Forces. 1998; 77(1):257–287.

Guo G, Harris KM. The mechanisms mediating the effects of poverty on children's intellectual development. Demography. 2000; 37(4):431–447. [PubMed: 11086569]

Hack M, Klein NK, Taylor HG. Long-term developmental outcomes of low birth weight infants. The Future of Children / Center for the Future of Children, the David and Lucile Packard Foundation. 1995; 5(1):176–196.

Heckman JJ. Skill Formation and the Economics of Investing in Disadvantaged Children. Science. 2006; 312(5782):1900–1902. [PubMed: 16809525]

Hopson LM, Lee E. Mitigating the effect of family poverty on academic and behavioral outcomes: The role of school climate in middle and high school. Children and Youth Services Review. 2011; 33(11):2221–2229.

Kerckhoff AC, Raudenbush SW, Glennie E. Education, cognitive skill, and labor force outcomes. Sociology of Education. 2001; 74(1):1–24.

Komro KA, Flay BR, Biglan A, Consortium PNR. Creating Nurturing Environments: A Science-Based Framework for Promoting Child Health and Development Within High-Poverty Neighborhoods. Clinical Child and Family Psychology Review. 2011; 14(2):111–134. [PubMed: 21468644]

Kramer MR, Cooper HL, Drews-Botsch CD, Waller LA, Hogue CR. Metropolitan isolation segregation and Black-White disparities in very preterm birth: a test of mediating pathways and variance explained. Social Science & Medicine (1982). 2010; 71(12):2108–2116. [PubMed: 20947234]

Lee, VE.; Burkam, DT. Inequality at the Starting Gate: Social Background Differences in Achievement as Children Begin School. Washington, DC: Economic Policy Institute; 2002. Retrieved from http://eric.ed.gov/?id=ED470551

McGowan JE, Alderdice FA, Holmes VA, Johnston L. Early childhood development of late-preterm infants: a systematic review. Pediatrics. 2011; 127(6):1111–1124. [PubMed: 21624885]

Messer LC, Laraia BA, Kaufman JS, Eyster J, Holzman C, Culhane J, O'Campo P. The development of a standardized neighborhood deprivation index. Journal of Urban Health: Bulletin of the New York Academy of Medicine. 2006; 83(6):1041–1062. [PubMed: 17031568]

Messer LC, Oakes JM, Mason S. Effects of socioeconomic and racial residential segregation on preterm birth: a cautionary tale of structural confounding. American Journal of Epidemiology. 2010; 171(6):664–673. [PubMed: 20139129]

Messer LC, Vinikoor LC, Laraia BA, Kaufman JS, Eyster J, Holzman C, O'Campo P. Socioeconomic domains and associations with preterm birth. Social Science & Medicine (1982). 2008; 67(8): 1247–1257. [PubMed: 18640759]

National Center for Education Statistics. Monitoring School Quality: An Indicators Report. 2000. Retrieved from http://nces.ed.gov/pubs2001/2001030.pdf

O'Campo P, Burke JG, Culhane J, Elo IT, Eyster J, Holzman C, Laraia BA. Neighborhood deprivation and preterm birth among non-Hispanic Black and White women in eight geographic areas in the United States. American Journal of Epidemiology. 2008; 167(2):155–163. [PubMed: 17989062]

Potijk MR, Kerstjens JM, Bos AF, Reijneveld SA, de Winter AF. Developmental delay in moderately preterm-born children with low socioeconomic status: risks multiply. The Journal of Pediatrics. 2013; 163(5):1289–1295. [PubMed: 23968750]

Pugliese M, Rossi C, Guidotti I, Gallo C, Della Casa E, Bertoncelli N, Ferrari F. Preterm birth and developmental problems in infancy and preschool age Part II: cognitive, neuropsychological and behavioural outcomes. Journal of Maternal-Fetal & Neonatal Medicine. 2013; 26(16):1653–1657. [PubMed: 23570550]

Rothman, K.; Lash, T.; Greenland, S. Modern Epidemiology. 3rd ed.. Lippincott Williams & Wilkins; 2012.

Sampson RJ, Sharkey P, Raudenbush SW. Durable effects of concentrated disadvantage on verbal ability among African-American children. Proceedings of the National Academy of Sciences of the United States of America. 2008; 105(3):845–852. [PubMed: 18093915]

Sastry N, Pebley AR. Family and neighborhood sources of socioeconomic inequality in children's achievement. Demography. 2010; 47(3):777–800. [PubMed: 20879688]

Simms V, Cragg L, Gilmore C, Marlow N, Johnson S. Mathematics difficulties in children born very preterm: current research and future directions. Archives of Disease in Childhood. Fetal and Neonatal Edition. 2013; 98(5):F457–F463. [PubMed: 23759519]

Turkheimer E, Haley A, Waldron M, D'Onofrio B, Gottesman II. Socioeconomic status modifies heritability of IQ in young children. Psychological Science. 2003; 14(6):623–628. [PubMed: 14629696]

Vanderweele TJ. Sample size and power calculations for additive interactions. Epidemiologic Methods. 2012; 1(1):159–188. [PubMed: 25473594]

VanderWeele TJ, Knol MJ. A tutorial on interaction. Epidemiologic Methods. 2014; 3:33–72.

Weisglas-Kuperus N, Baerts W, Smrkovsky M, Sauer PJ. Effects of biological and social factors on the cognitive development of very low birth weight children. Pediatrics. 1993; 92(5):658–665. [PubMed: 7692381]

Williams BL, Dunlop AL, Kramer M, Dever BV, Hogue C, Jain L. Perinatal origins of first-grade academic failure: role of prematurity and maternal factors. Pediatrics. 2013; 131(4):693–700. [PubMed: 23530177]

Research highlights

- Preterm children more likely to fail Georgia's 1st grade standardized tests
- Gradient effect showed increased risk of test failure with earlier birth
- Living in more deprived neighborhood was modest predictor of test failure
- Neighborhood deprivation modifies effect of preterm birth on school achievement
- Double-jeopardy of preterm birth and area-based deprivation increases risk

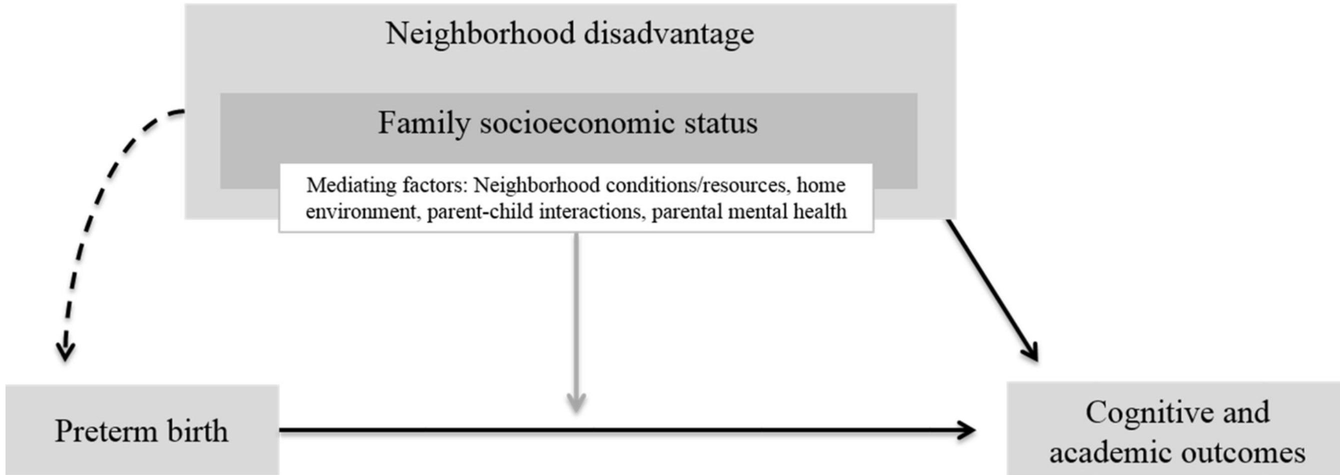

Figure 1. Conceptual framework for relationships between preterm birth, socioeconomic status (SES), and cognitive and academic outcomes

The solid black lines indicate the recognized associations of (a) SES (e.g., neighborhood deprivation, family SES) and (b) preterm birth with children's cognitive and academic outcomes. The solid gray line indicates hypothesized effect modification of the relationship between preterm birth and cognitive and academic outcomes by SES; in these analyses, we test effect modification by neighborhood deprivation after controlling for indicators of family-level SES. The dashed black line indicates the recognized association between SES (e.g., neighborhood deprivation, family SES) and preterm birth; however, this arrow is not controlled in our analysis due to our interest in estimating the independent effect of neighborhood deprivation after the preterm birth has occurred.

Table 1

Characteristics of the study cohort.

	Total	Gestational Age					Neighborhood Deprivation Index	
	Total	Early preterm	Moderate preterm	Late preterm	Term			
	N (%)	N (%)	N (%)	N (%)	N (%)	p-value	Mean (SD)	p-value
Total	327,698	1,127 (0.3)	6,276 (1.9)	25,884 (7.9)	294,411 (89.8)		−0.09 (0.90)	
Maternal age at birth								
15–17 years	17,330 (5.3)	83 (0.5)	455 (2.6)	1,675 (9.7)	15,117 (87.2)		0.35 (0.89)	
18–19 years	31,954 (9.8)	138 (0.4)	739 (2.3)	2,744 (8.6)	28,333 (88.7)		0.24 (0.86)	
20–24 years	95,227 (29.1)	292 (0.3)	1,803 (1.9)	7,637 (8.0)	85,495 (89.8)		0.15 (0.86)	
25–29 years	87,440 (26.7)	273 (0.3)	1,429 (1.6)	6,288 (7.2)	79,450 (90.9)	<.0001	−0.16 (0.84)	<.0001
30–34 years	62,865 (19.2)	210 (0.3)	1,112 (1.8)	4,648 (7.4)	56,895 (90.5)		−0.44 (0.85)	
35–39 years	27,971 (8.5)	105 (0.4)	603 (2.2)	2,421 (8.7)	24,842 (88.8)		−0.50 (0.88)	
40–53 years	4,911 (1.5)	26 (0.5)	135 (2.8)	471 (9.6)	4,279 (87.1)		−0.43 (0.93)	
Maternal race/ethnicity								
White non-Hispanic	179,245 (54.7)	320 (0.2)	2,491 (1.4)	12,763 (7.1)	163,671 (91.3)		−0.42 (0.72)	
Black non-Hispanic	116,544 (35.6)	747 (0.6)	3,372 (2.9)	11,165 (9.6)	101,260 (86.9)	<.0001	0.41 (0.94)	<.0001
Hispanic	31,909 (9.7)	60 (0.2)	413 (1.3)	1,956 (6.1)	29,480 (92.4)		−0.05 (0.80)	
Maternal education at birth								
Less than high school	82,097 (25.4)	270 (0.3)	1,828 (2.2)	7,133 (8.7)	72,866 (88.8)		0.28 (0.87)	
Completed high school	112,913 (35.0)	436 (0.4)	2,260 (2.0)	9,169 (8.1)	101,048 (89.5)	<.0001	0.05 (0.85)	<.0001
Up to 3 years postsecondary	65,796 (20.4)	258 (0.4)	1,259 (1.9)	5,153 (7.8)	59,126 (89.9)		−0.21 (0.83)	
4 or more years postsecondary	62,082 (19.2)	146 (0.2)	852 (1.4)	4,097 (6.6)	56,987 (91.8)		−0.72 (0.75)	
Missing	4,810	17 (0.4)	77 (1.6)	332 (6.9)	4,384 (91.1)		−0.13 (0.90)	
Medicaid status								
Yes	155,126 (47.3)	598 (0.4)	3,395 (2.2)	13,241 (8.5)	137,892 (88.9)	<.0001	0.25 (0.86)	<.0001
No	172,572 (52.7)	529 (0.3)	2,881 (1.7)	12,643 (7.3)	156,519 (90.7)		−0.40 (0.82)	
Marital status								
Unmarried	125,213 (38.2)	631 (0.5)	3,292 (2.6)	11,415 (9.1)	109,875 (87.8)	<.0001	0.33 (0.92)	<.0001
Married	202,467 (61.8)	496 (0.2)	2,982 (1.5)	14,469 (7.2)	184,520 (91.1)		−0.36 (0.78)	
Missing	18	0 (0.0)	2 (11.1)	0 (0.0)	16 (88.9)		−0.23 (0.53)	

	Total	Gestational Age					Neighborhood Deprivation Index	
		Early preterm	Moderate preterm	Late preterm	Term			
	N (%)	N (%)	N (%)	N (%)	N (%)	p-value	Mean (SD)	p-value
Smoking status during pregnancy								
Yes	30,410 (9.3)	107 (0.4)	728 (2.4)	2,901 (9.5)	26,674 (87.7)	<.0001	0.00 (0.79)	<.0001
No	295,593 (90.7)	1,014 (0.3)	5,492 (1.9)	22,838 (7.7)	266,249 (90.1)		−0.10 (0.91)	
Missing	1,695	6 (0.4)	56 (3.3)	145 (8.5)	1,488 (87.8)		−0.18 (0.80)	
Child's sex								
Male	165,933 (50.6)	546 (0.3)	3,275 (2.0)	13,693 (8.2)	148,419 (89.5)	<.0001	−0.09 (0.90)	0.33
Female	161,765 (49.4)	581 (0.4)	3,001 (1.9)	12,191 (7.5)	145,992 (90.2)		−0.09 (0.90)	
Child age at CRCT								
6	118,219 (36.1)	347 (0.3)	2,185 (1.9)	9,326 (7.9)	106,361 (90.0)		−0.10 (0.90)	
7	202,092 (61.7)	687 (0.3)	3,842 (1.9)	15,798 (7.8)	181,765 (89.9)	<.0001	−0.10 (0.90)	<.0001
8	7,387 (2.2)	93 (1.3)	249 (3.4)	760 (10.3)	6,285 (85.1)		0.24 (0.92)	
First grade CRCT mathematics								
Failed	41,657 (12.7)	371 (0.9)	1,285 (3.1)	3,927 (9.4)	36,074 (86.6)	<.0001	0.23 (0.89)	<.0001
Passed	285,659 (87.3)	754 (0.3)	4,980 (1.7)	21,923 (7.7)	258,002 (90.3)		−0.14 (0.89)	
Missing	382	2 (0.5)	11 (2.9)	34 (8.9)	335 (87.7)		−0.03 (0.92)	

Table 2

Risk of CRCT mathematics failure, stratified by gestational age and Neighborhood Deprivation Index.

	Total		Quartile 1 (least deprived)		Quartile 2		Quartile 3		Quartile 4 (most deprived)	
	n failed/total	**%**	**n failed/total**	**%**	**n failed/total**	**%**	**n failed/total**	**%**	**n failed/total**	**%**
Total	41,657/327,316	12.7%	5,430/81,946	6.6%	9,420/81,725	11.5%	11,398/81,807	13.9%	15,409/81,838	18.8%
Term	36,074/294,076	12.3%	4,791/74,967	6.4%	8,273/73,990	11.2%	9,869/73,172	13.5%	13,141/71,947	18.3%
Late preterm	3,927/25,850	15.2%	457/5,628	8.1%	844/6,114	13.8%	1,048/6,709	15.6%	1,578/7,399	21.3%
Moderate preterm	1,285/6,265	20.5%	152/1,183	12.9%	239/1,385	17.3%	360/1,608	22.4%	534/2,089	25.6%
Early preterm	371/1,125	33.0%	30/168	17.9%	64/236	27.1%	121/318	38.1%	156/403	38.7%

Table 3

Associations between preterm birth, neighborhood deprivation, and CRCT mathematics failure (main effects models).

	Failed	Total	Unadjusted[a]		Model I[b]		Model II (fully adjusted)[c]	
	N (%)	N	RD (95% CI)	RR (95% CI)	RD (95% CI)	RR (95% CI)	RD (95% CI)	RR (95% CI)
Exposures								
Gestational age								
Early preterm	371 (33.0)	1,125	0.207 (0.180, 0.234)	2.69 (2.47, 2.92)	0.167 (0.140, 0.193)	2.08 (1.91, 2.27)	0.168 (0.142, 0.1944)	2.07 (1.90, 2.25)
Moderate preterm	1,285 (20.5)	6,265	0.082 (0.072, 0.093)	1.67 (1.59, 1.76)	0.053 (0.044, 0.062)	1.39 (1.32, 1.46)	0.049 (0.040, 0.058)	1.36 (1.29, 1.42)
Late preterm	3,927 (15.2)	25,850	0.029 (0.025, 0.034)	1.24 (1.20, 1.28)	0.013 (0.009, 0.016)	1.13 (1.10, 1.17)	0.009 (0.006, 0.013)	1.11 (1.08, 1.15)
Term	36,074 (12.3)	294,076	Ref	Ref	Ref	Ref	Ref	Ref
1 unit increase in NDI			0.055 (0.053, 0.058)	1.43 (1.40, 1.46)	0.017 (0.015, 0.019)	1.11 (1.09, 1.13)	0.006 (0.005, 0.008)	1.03 (1.01, 1.05)
Covariates								
Maternal age at birth								
15–17 years	3,357 (19.4)	17,307	0.084 (0.077, 0.091)	1.76 (1.69, 1.83)	0.024 (0.017, 0.030)	1.13 (1.09, 1.18)	−0.036 (−0.043, −0.029)	0.78 (0.75, 0.82)
18–19 years	5,527 (17.3)	31,904	0.063 (0.058, 0.068)	1.57 (1.51, 1.63)	0.015 (0.011, 0.020)	1.09 (1.05, 1.12)	−0.018 (−0.023, −0.014)	0.87 (0.84, 0.90)
20–24 years	14,850 (15.6)	95,097	0.046 (0.042, 0.049)	1.42 (1.37, 1.46)	0.014 (0.011, 0.017)	1.08 (1.05, 1.11)	−0.002 (−0.005, 0.000)	0.97 (0.95, 0.99)
25–29 years	9,637 (11.0)	87,349	Ref	Ref	Ref	Ref	Ref	Ref
30–34 years	5,294 (8.4)	62,812	−0.026 (−0.030, −0.023)	0.76 (0.73, 0.79)	−0.005 (−0.007, −0.003)	0.90 (0.87, 0.93)	0.001 (−0.001, 0.003)	0.98 (0.95, 1.01)
35–39 years	2,465 (8.8)	27,941	−0.022 (−0.027, −0.018)	0.80 (0.76, 0.84)	−0.003 (−0.006, −0.000)	0.93 (0.89, 0.97)	0.002 (−0.001, 0.005)	1.01 (0.97, 1.05)
40–53 years	527 (10.7)	4,906	−0.003 (−0.012, 0.006)	0.97 (0.89, 1.06)	0.006 (−0.001, 0.013)	1.07 (0.98, 1.16)	0.011 (0.005, 0.018)	1.14 (1.05, 1.24)
Maternal race/ethnicity								
White non-Hispanic	13,549 (7.6)	179,057	Ref	Ref	Ref	Ref	Ref	Ref
Black non-Hispanic	22,334 (19.2)	116,396	0.116 (0.111, 0.121)	2.54 (2.44, 2.64)	0.069 (0.065, 0.073)	1.87 (1.81, 1.94)	0.075 (0.071, 0.078)	1.96 (1.90, 2.02)
Hispanic	5,774 (18.1)	31,863	0.106 (0.098, 0.113)	2.39 (2.28, 2.52)	0.084 (0.077, 0.091)	2.11 (2.01, 2.20)	0.044 (0.038, 0.050)	1.56 (1.50, 1.64)
Maternal education at birth								
Less than high school	17,168 (20.9)	81,960	0.177 (0.172, 0.182)	6.40 (5.98, 6.85)			0.124 (0.119, 0.128)	4.38 (4.13, 4.65)
Completed high school	15,952 (14.1)	112,784	0.109 (0.105, 0.112)	4.32 (4.05, 4.61)			0.059 (0.057, 0.062)	3.10 (2.94, 3.28)
Up to 3 years postsecondary	5,660 (8.6)	65,748	0.053 (0.050, 0.056)	2.63 (2.47, 2.80)			0.019 (0.017, 0.021)	2.04 (1.93, 2.16)
4 or more years postsecondary	2,031 (3.3)	62,022	Ref	Ref			Ref	Ref
Medicaid status								

	Failed	Total	Unadjusted[a]		Model I[b]		Model II (fully adjusted)[c]	
	N (%)	N	RD (95% CI)	RR (95% CI)	RD (95% CI)	RR (95% CI)	RD (95% CI)	RR (95% CI)
Yes	27,641 (17.8)	154,916	0.097 (0.093, 0.101)	2.19 (2.12, 2.28)	0.044 (0.041, 0.047)	1.44 (1.40, 1.48)	0.023 (0.020, 0.026)	1.22 (1.19, 1.25)
No	14,016 (8.1)	172,400	Ref	Ref	Ref	Ref	Ref	Ref
Marital status								
Unmarried	23,975 (19.2)	125,041	0.104 (0.100, 0.108)	2.19 (2.12, 2.27)	0.032 (0.028, 0.035)	1.25 (1.22, 1.28)	0.023 (0.020, 0.027)	1.15 (1.12, 1.18)
Married	17,680 (8.7)	202,257	Ref	Ref	Ref	Ref	Ref	Ref
Smoking status during pregnancy								
Yes	4,463 (14.7)	30,372	0.022 (0.017, 0.027)	1.17 (1.13, 1.22)	0.026 (0.022, 0.031)	1.33 (1.28, 1.37)	0.004 (0.000, 0.008)	1.12 (1.08, 1.15)
No	36,985 (12.5)	295,254	Ref	Ref	Ref	Ref	Ref	Ref
Child's sex								
Male	23,266 (14.0)	165,726	Ref	Ref	Ref	Ref	Ref	Ref
Female	18,391 (11.4)	161,590	−0.027 (−0.029, −0.024)	0.81 (0.80, 0.83)	−0.019 (−0.021, −0.017)	0.81 (0.79, 0.82)	−0.015 (−0.017, −0.013)	0.81 (0.79, 0.82)
Child age at CRCT								
6	16,839 (14.3)	118,108						
7	22,402 (11.1)	201,834						
8	2,416 (32.8)	7,374						
1 unit increase in child age			−0.003 (−0.006, −0.000)	0.97 (0.95, 0.99)	−0.003 (−0.005, −0.001)	0.94 (0.92, 0.95)	−0.002 (−0.004, 0.000)	0.92 (0.90, 0.93)

Note: All models clustered by census tract.

[a] Unadjusted risk differences and risk ratios for each exposure or covariate.

[b] Model I is adjusted for all covariates except maternal education.

[c] Model II is fully adjusted.

Table 4

Associations between preterm birth, neighborhood deprivation, and CRCT mathematics failure (interaction models).

	Unadjusted[a]			Model I[b]			Model II (fully adjusted)[c]		
	Additive	Multiplicative		Additive	Multiplicative		Additive	Multiplicative	
Regression coefficients	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**
Gestational age									
Early preterm	0.181 (0.154, 0.208)	0.94 (0.85, 1.03)	0.14 (−0.07, 0.37)	0.159 (0.133, 0.185)	0.78 (0.69, 0.87)	−0.07 (−0.25, 0.11)	0.159 (0.133, 0.185)	0.77 (0.68, 0.87)	−0.14 (−0.29, 0.04)
Moderate preterm	0.071 (0.061, 0.080)	0.48 (0.42, 0.53)	0.01 (−0.09, 0.10)	0.054 (0.044, 0.063)	0.36 (0.31, 0.42)	−0.08 (−0.16, 0.00)	0.050 (0.041, 0.059)	0.34 (0.29, 0.39)	−0.09 (−0.17, 0.02)
Late preterm	0.023 (0.019, 0.028)	0.19 (0.16, 0.22)	0.01 (−0.04, 0.06)	0.015 (0.011, 0.019)	0.14 (0.11, 0.17)	−0.03 (−0.07, 0.01)	0.013 (0.009, 0.017)	0.12 (0.09, 0.15)	−0.03 (−0.07, 0.01)
Term	Ref	Ref		Ref	Ref		Ref	Ref	
Neighborhood Deprivation Index (NDI)									
1 unit increase in NDI	0.054 (0.051, 0.057)	0.36 (0.34, 0.39)		0.017 (0.015, 0.019)	0.11 (0.09, 0.13)		0.006 (0.001, 0.004)	0.04 (0.02, 0.06)	
Interaction of Gestational age and NDI									
Early preterm*NDI	0.029 (0.002, 0.056)	−0.16 (−0.23, −0.08)		0.043 (0.018, 0.069)	−0.09 (−0.17, −0.01)		0.048 (0.022, 0.073)	−0.09 (−0.17, −0.01)	
Moderate preterm*NDI	0.004 (−0.007, 0.014)	−0.12 (−0.17, −0.07)		0.011 (0.002, 0.021)	−0.09 (−0.14, −0.03)		0.015 (0.006, 0.025)	−0.07 (−0.13, −0.02)	
Late preterm*NDI	0.004 (−0.001, 0.009)	−0.05 (−0.08, −0.02)		0.007 (0.003, 0.011)	−0.04 (−0.07, −0.01)		0.008 (0.004, 0.011)	−0.03 (−0.06, 0.00)	
p-value for interaction	0.057	<.0001		<.0001	<.001		<.0001	<.01	
Estimated effect measures	**RD (95% CI)**	**RR (95% CI)**		**RD (95% CI)**	**RR (95% CI)**		**RD (95% CI)**	**RR (95% CI)**	
Effect of preterm birth at low deprivation (NDI = −1)									
Early preterm	0.152 (0.113, 0.191)	3.01 (2.62, 3.46)		0.116 (0.079, 0.152)	2.39 (2.08, 2.76)		0.111 (0.075, 0.147)	2.36 (2.03, 2.75)	
Moderate preterm	0.067 (0.053, 0.080)	1.81 (1.67, 1.97)		0.042 (0.030, 0.055)	1.57 (1.44, 1.71)		0.035 (0.023, 0.047)	1.51 (1.38, 1.65)	
Late preterm	0.019 (0.014, 0.024)	1.27 (1.21, 1.33)		0.008 (0.004, 0.012)	1.20 (1.14, 1.26)		0.005 (0.002, 0.008)	1.16 (1.10, 1.22)	
Term	Ref	Ref		Ref	Ref		Ref	Ref	
Effect of preterm birth at average deprivation (NDI = 0)									
Early preterm	0.181 (0.154, 0.208)	2.57 (2.35, 2.81)		0.159 (0.133, 0.185)	2.19 (1.00, 2.40)		0.159 (0.133, 0.185)	2.17 (1.97, 2.38)	
Moderate preterm	0.071 (0.061, 0.080)	1.61 (1.53, 1.70)		0.054 (0.044, 0.063)	1.44 (1.37, 1.52)		0.050 (0.041, 0.059)	1.40 (1.33, 1.48)	
Late preterm	0.023 (0.019, 0.028)	1.21 (1.17, 1.24)		0.015 (0.011, 0.019)	1.15 (1.11, 1.18)		0.013 (0.009, 0.017)	1.13 (1.09, 1.16)	
Term	Ref	Ref		Ref	Ref		Ref	Ref	
Effect of preterm birth at high deprivation (NDI = 1)									
Early preterm	0.210 (0.173, 0.247)	2.20 (2.01, 2.40)		0.202 (0.166, 0.239)	2.00 (1.83, 2.20)		0.206 (0.169, 0.243)	1.99 (1.81, 2.19)	

Author Manuscript
Author Manuscript
Author Manuscript

	Unadjusted[a]			Model I[b]			Model II (fully adjusted)[c]		
	Additive	Multiplicative		Additive	Multiplicative		Additive	Multiplicative	
Regression coefficients	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**	**β (95% CI)**	**β (95% CI)**	**RERI[d] (95% CI)**
Moderate preterm	0.075 (0.059, 0.090)	1.43 (1.35, 1.52)		0.065 (0.050, 0.080)	1.32 (1.24, 1.40)		0.065 (0.051, 0.080)	1.30 (1.23, 1.38)	
Late preterm	0.027 (0.019, 0.035)	1.15 (1.10, 1.19)		0.022 (0.014, 0.029)	1.10 (1.06, 1.15)		0.020 (0.013, 0.027)	1.09 (1.05, 1.14)	
Term	Ref	Ref		Ref	Ref		Ref	Ref	

Note: All models clustered by census tract.

[a]Unadjusted risk differences and risk ratios for each exposure.

[b]Model I is adjusted for all covariates except maternal education.

[c]Model II is fully adjusted.

[d]Relative excess risk due to interaction between preterm birth and 1 SD increase in NDI (from 0 to 1), for each preterm birth category.