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Abstract

Prior research has found that financial investments in North Carolina's pre-kindergarten (pre-K) program generated positive effects on student reading and math achievement through eighth grade (Bai et al., 2020). The current study examined the interaction between NC Pre-K funding and two key dimensions of the subsequent educational environment students experience in their school districts: average achievement and achievement growth. In relation to student reading and math achievement in eighth grade, the benefits of NC Pre-K funding were found to be additive to the benefits of school-district average achievement. The benefits of NC Pre-K funding were also found to interact with the benefits of school-district achievement growth such that the NC Pre-K effect was larger in school districts with lower rates of growth in academic achievement. These findings suggest that public investments in early childhood education may be particularly beneficial in the long term for children who subsequently experience low-growth schooling environments compared to children in high-growth environments.

Keywords: Early childhood education; long-term effects; reading; mathematics.

Introduction

Public investments in high-quality early childhood education (ECE) programs can result in substantial benefits to society, especially if those investments target children from families who experience economic insecurity (Heckman, 2006). The short-term benefits of ECE include enhanced learning of school readiness skills, which can translate into longer-term improvements to academic achievement during school (e.g., Campbell et al., 2002). However, not all children display lasting benefits of ECE. We sought to understand whether the long-term effects of ECE are enhanced or diminished by the educational environments children experience during K-8 schooling, a topic of interest to both policy and academic audiences alike (Bailey et al., 2017; Phillips et al., 2017).[1] Yet, there remains some uncertainty regarding the mechanisms by which educational environments during school will moderate the long-term effects of ECE.

We frame our study between the leading hypotheses regarding the interaction between ECE and subsequent educational environments: *dynamic complementarity* and *dynamic substitutability* (Bailey, Duncan, et al., 2020). Complementarity asserts that ECE will be most effective in the long term in the context of higher-quality educational environments as children progress through school. Alternatively, substitutability posits that ECE will be most effective in the long term in the context of lower-quality school environments. Yet a third hypothesis predicts the *additive* rather than interactive effects of ECE and subsequent educational environments. According to the *additivity* hypothesis, the effect of ECE will persist in the long term under all conditions of the subsequent educational environment, which also exerts a positive, independent impact on children's development. Findings from the existing research

[1] We refer to ECE program effects on eighth grade outcomes as "long-term" because students have entered adolescence. Effects on student outcomes during elementary school are often referred to as medium-term (e.g., Unterman & Weiland, 2020).

base are mixed and do not provide a clear consensus regarding the interaction or additivity between the long-term effects of ECE and subsequent educational environments (Bailey, Jenkins, et al., 2020).

Our research team has previously examined the long-term effect of financial investments in North Carolina's pre-kindergarten (pre-K) program (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013; Muschkin et al., 2015). Most relevant to the current study, we found that increases in NC Pre-K funding produced positive effects on student reading and math achievement through eighth grade (Bai et al., 2020). The unique contribution of the current study was to examine whether the long-term effect of NC Pre-K is moderated by the educational environments children subsequently experience in NC public school districts. We measured educational environments for students along two dimensions at the district level: (1) the average level of academic achievement and (2) the average rate of growth in academic achievement. We tested for moderation of the NC Pre-K program funding effect by both measures. The results of this study offer new evidence concerning the role of school contexts in contributing to the long-term benefits of ECE.

North Carolina's Pre-K Program

NC Pre-K (previously known as More At Four) is a state-funded educational program designed to enhance the school readiness skills of 4-year-old children prior to kindergarten entry.[2] When the NC Pre-K program was established in 2001, NC was among the latter half of states to adopt a public pre-K program (Cohen-Vogel et al., 2020). The program grew quickly during the following years. By 2010, an estimated 24% of the state's 4-year-old population was

[2] Between 2001 and 2010, the NC Pre-K program was administered by the NC Department of Public Instruction (DPI) and known as the More at Four program. In 2011, the NC General Assembly transferred the program to the Division of Child Development and Early Education (DCDEE) in the NC Department of Health and Human Services (DHHS) and the program was renamed as the NC Pre-K program.

enrolled in the program (*N* = 31,197; Barnett et al., 2010). That proportion has remained relatively consistent over time (e.g., an estimated 24% served in 2019; Friedman-Krauss et al., 2020).

Since its inception, the NC Pre-K program has maintained high quality standards. For example, during its first year of operation, the NC Pre-K program met 7 of 10 quality benchmarks established by the National Institute of Early Education Research (e.g., class size and staff-child ratios, teacher qualifications and training, learning standards, health and nutrition services, and program monitoring; Barnett et al., 2003). Just four years later, the NC Pre-K program had increased its standards to meet all 10 quality benchmarks (Barnett et al., 2006) and continues to maintain these standards (Friedman-Krauss et al., 2020). Moreover, NC Pre-K has sought to promote uniformity in program standards across the state through quality monitoring and continuous quality improvement initiatives. For example, all NC Pre-K providers are required to maintain a four- or five-star license—the highest quality ratings under North Carolina’s child care licensing system.

The NC Pre-K program targets eligible four-year-old children whose gross family income is at or below 75% of the state median income, or if the child has at least one of the following factors: educational or developmental delay, an identified disability, a chronic health condition, or limited English proficiency (Barnett et al., 2010).[3] Participating children receive a NC Pre-K funded “slot” in a variety of classroom-based settings that meet the state quality standards, including public schools, Head Start, and private child care centers (both for-profit and nonprofit). However, a key feature of the NC Pre-K program concerns the composition of children in classrooms being blended with individual children who do and do not receive NC

[3] After our study period (i.e., through 2010), NC Pre-K program eligibility was extended to children with a parent serving in the military.

Pre-K funded slots. During the course of our study period, estimates suggest that two-thirds of children who were enrolled in participating classrooms received an NC Pre-K funded slot, while one-third of children in participating classrooms were not directly funded by the NC Pre-K program (Peisner-Feinberg et al., 2006). Therefore, the benefits of the NC Pre-K funds could spill over to children who were not directly funded by the program but were enrolled in the same classroom as a child receiving an NC Pre-K-funded slot, because these classrooms were required to meet a variety of NC Pre-K program standards designed to ensure a high-quality educational experience for all children. Through this strategy of funding slots for individual children in mixed classroom settings, the program seeks to promote high-quality preschool not only for the funded children, but also for other children enrolled in the same classrooms.

Consistent with our previous studies of NC Pre-K (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013; Muschkin et al., 2015), the current study leveraged the differential rollout of funding for the NC Pre-K program across North Carolina (described in greater detail below). We used variability in the amount of funding that was allocated to communities over time in order to identify the community-wide effect of NC Pre-K. With this approach, we examined the effect of NC Pre-K funding on the population of students in North Carolina who could have received direct benefits from an NC Pre-K funded slot or benefited through spillover effects.

Educational Environments During School

Reardon (2019) has operationalized two dimensions of the educational environment children experience during school: (1) the average level of academic achievement among third grade students in the school district (i.e., average achievement) and (2) the average rate of growth in academic achievement among students in the school district as they progress from third to eighth grade (i.e., achievement growth). These measures were derived from standardized test score data from students across all public school districts in the U.S. In that study, the correlation between average achievement and achievement growth was very weak (r = –0.13). Additionally, average achievement was highly correlated with a measure of community-wide socioeconomic status (r = 0.68), while achievement growth was moderately correlated (r = 0.32). These correlations provide evidence of divergent validity and suggest that average achievement and achievement growth capture distinct dimensions of the educational environment during school. While average achievement may reflect a broad range of educational inputs available to students in their school and communities (e.g., neighborhood characteristics, average family resources in a community), achievement growth may better capture the educational inputs uniquely related to schools and schooling.

In the current study, we measured average achievement and achievement growth among NC's public school districts. The NC public school system is one in which student achievement measures are commonly used for high-stakes accountability and performance monitoring. Following Reardon (2019), we also examined school districts rather than schools as the unit of analysis for the educational environment during school. We note that there are many ways in which school districts can directly and indirectly shape the educational experiences and outcomes of individual students. For example, school-district administrators set policies and make important decisions that directly influence the structural characteristics of schools, such as the provision of classroom curriculum and professional development; the recruitment, retention, and salaries of teachers and principals; as well as the design and implementation of evaluation systems (Chenoweth, 2021; Hanushek et al., 2004; Polikoff, 2018). In extreme cases, school-district administrators can fundamentally reform and/or reorganize schools through school closures, consolidations, and the implementation of accountability systems. School-district administrators can also influence the culture of school environments. For example, case studies by Chenoweth (2021) described effective school districts as having a culture in which the leadership cultivates the belief that all children are capable of success and that the adults are responsible for ensuring children succeed (p. 131). Indeed, a comprehensive case study of Chicago Public Schools identified *effective leaders* as the most critical ingredient in building a culture of school improvement (Bryk et al., 2010). Quantitative research also provides evidence of the role that school districts can play in shaping student learning outcomes (see review by Blazar & Schueler, 2022). Perhaps most relevant to the current study, Chingos et al. (2015) analyzed statewide data from North Carolina during the 2009-10 school year. They found that a measure of school district effectiveness was associated with a 0.11 and 0.14 standard deviation unit increase in student reading and math test scores, respectively, among fourth- and fifth-grade students. This difference was equivalent to a boost of roughly ten to eleven weeks of additional learning. In sum, school-district leadership can shape the structural organization and culture of schools, and, in turn, these features of the school environment can influence students' academic skill development during school.

The Long-Term Effects of ECE on Academic Achievement

A robust body of evidence suggests that ECE can have positive, short-term effects on children's academic readiness for school (Phillips et al., 2017; Yoshikawa et al., 2013). While some studies have found that ECE effects on academic achievement outcomes continue to be evident throughout childhood and into adolescence, other studies document evidence of diminishing ECE effects that do not persist in the long-term. In this section, we review studies related to ECE effects on academic achievement outcomes (e.g., reading and math test scores).[4]

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[4] We note that ECE programming can also have positive long-term effects on broader educational outcomes related to school progress (e.g., grade retention) and overall educational attainment (e.g., high school graduation; McCoy et

Recent studies provide a wealth of evidence that scaled-up ECE programs can positively impact children's early academic skill development in the short run. This includes random-assignment studies (Lipsey et al., 2018; Peisner-Feinberg et al., 2019; Puma et al., 2010), as well as quasi-experimental studies comparing children who participate in ECE programs to non-participating peers (e.g., propensity score matching, regression discontinuity; Barnett et al., 2018; Bassok et al., 2019; Gormley et al., 2008; Peisner-Feinberg & Schaaf, 2011; Peisner-Feinberg et al., 2014; Weiland & Yoshikawa, 2013).

Despite strong evidence of positive short-term effects, the evidence becomes mixed in studies that follow children through school. Random-assignment studies of modern-day ECE programs have all documented diminishing effects on academic achievement outcomes that largely disappear during the early elementary grades (Lipsey et al., 2018; Peisner-Feinberg et al., 2020; Puma et al., 2012). Surprisingly, the random-assignment study of Tennessee's state-funded pre-K program eventually documented negative effects on academic achievement outcomes during the elementary school grades (Lipsey et al., 2018) and these negative effects continued to be evident through sixth grade (Durkin et al., 2022). Some quasi-experimental studies of treatment-comparison groups also document evidence of diminishing effects on academic achievement outcomes during school (Amadon et al., 2022; Bassok et al., 2019; Hill et al., 2015; Weiland et al., 2019). However, other quasi-experimental studies document evidence of positive effects through elementary school (Bassok et al., 2019; Hill et al., 2015), middle school (Ansari, 2018; Gormley et al., 2018; Phillips et al., 2016), and high school (Barnett & Jung, 2021). The effects of NC Pre-K have also been investigated in a series of quasi-experimental studies that compare program participants and non-participants—documenting positive effects on academic

al., 2017), even when long-term effects on academic achievement are not observed (e.g., Gray-Lobe et al., 2021). However, we focus exclusively on academic achievement outcomes in the current study.

achievement outcomes at school entry (Peisner-Feinberg & Schaaf, 2011) as well as positive effects on academic achievement outcomes through kindergarten (Peisner-Feinberg et al., 2017; Peisner-Feinberg & Schaaf, 2011) and third grade (Peisner-Feinberg & Schaaf, 2010).

A separate body of quasi-experimental research has examined variation in the rollout of ECE programming using the difference-in-difference design. These studies all focus on longer-term effects and measure population-wide effects that could be conferred through direct benefits to program participants as well as spillover effects to non-participants. For example, a series of studies conducted by our research team has examined the rollout of financial investments in NC Pre-K across North Carolina's 100 counties over multiple years (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013; Muschkin et al., 2015).[5] By leveraging between-community variation as well as within-community variation in the rollout of funding over time, these studies have documented positive effects of NC Pre-K funding exposure on student reading and math outcomes that were evident in third grade and continued to persist through eighth grade. Separate studies have also documented positive, long-term, and population-wide effects on academic achievement outcomes resulting from the rollout of state-funded pre-K programs in Georgia (Cascio & Schanzenbach, 2013; Fitzpatrick, 2008), Oklahoma (Cascio & Schanzenbach, 2013), and South Carolina (Williams, 2019), as well as the rollout of the federal Head Start preschool program (Kose, 2021).

In sum, there is mixed evidence concerning the long-term effects of ECE on academic skill development, leading to an interest in understanding the educational experiences children

[5] We note that our previous research has also examined the effects of funding for North Carolina's Smart Start program, which is a broad ranging early childhood initiative focused on child care, family support, and child health/wellbeing. However, Smart Start is not explicitly an ECE program and, therefore, is not the focus of the current study that concerns ECE and subsequent educational environments. However, we continue to control for Smart Start funding in our analyses (described in the Measures section below).

have after they graduate from their ECE programs and progress on through school. A question that has not yet been resolved concerns whether subsequent educational environments play a role in determining if ECE program effects will persist in the long term.

The Long-Term Effects of ECE and Subsequent Educational Environments During School

There may be certain conditions under which ECE program effects are more or less likely to persist in the long run. One hypothesis suggests that the long-term effects of ECE will be *larger* in the context of *higher*-quality educational environments during school (Bailey et al., 2017; Cunha et al., 2006; Phillips et al., 2017). Commonly referred to as *dynamic complementarity*, this hypothesis is rooted in economic theory of human capital formation which suggests that early investments in children's skill development are not productive in the long-run unless they are followed up by later investments across the lifespan (Cunha et al., 2006). In the education research literature, complementarity is called the *sustaining environments* hypothesis (Bailey et al., 2017). According to this hypothesis, the short-term effects of ECE can carry over into long-term effects, but only if higher-quality schooling enables children to build on the skills they gained through ECE and acquire more advanced skills during school.

An alternative hypothesis—*dynamic substitutability*—suggests that the long-term effects of ECE will be *larger* in the context of lower-quality educational environments during school and *smaller* in higher-quality educational environments (Bailey, Duncan, et al., 2020). Substitutability implies that the benefits of ECE will buffer children against lower-quality educational environments during school (Abenavoli, 2019; Bailey, Duncan, et al., 2020). For example, Abenavoli (2019) describes how high-quality ECE programming may promote resilience among children who subsequently enroll in lower-quality school environments. When examining the interaction between educational inputs across preschool and school, the substitutability hypothesis suggests that children with ECE program exposure will be better off relative to their peers without ECE exposure in lower-quality school environments (i.e., a positive effect of ECE in lower-quality school environments). Reciprocally, higher-quality school environments will provide a greater boost to the skill development of children who missed out on ECE—enabling them to catch up to their peers with previous ECE exposure (Abenavoli, 2019; Bailey, Duncan, et al., 2020).

While the two previous hypotheses infer the existence of a interaction between ECE and educational environments during school, the *additivity* hypothesis predicts no such interaction (Bailey, Jenkins, et al., 2020). According to the *additivity* hypothesis, the long-term effects of ECE are neither enhanced nor diminished by the subsequent educational environment. Simultaneously, the subsequent educational environment exerts a positive, developmentally promotive effect that is independent of the ECE effect. The additivity hypothesis suggests that ECE and the subsequent educational environment both contribute to promoting children's development in a supplemental, but not interactive way.

Statistically, all three hypotheses assume positive main effect coefficients for ECE and the subsequent educational environment. However, these hypotheses differ in their expectation of the coefficient for the interaction between ECE and subsequent educational inputs. While the complementarity hypothesis predicts a positive interaction between these two inputs, the substitutability hypothesis predicts by a negative interaction, and the additivity hypothesis expects no reliable interaction (Bailey, Jenkins, et al., 2020). Across studies examining how subsequent school environments moderate the long-term effects of ECE, a recent meta-analyses found limited evidence of interactions—complementarity or substitutability (Bailey, Jenkins, et al., 2020). Instead, there appeared to be more evidence of subsequent educational environments being additive, not interactive with ECE (Bailey, Jenkins, et al., 2020). However, there are many limitations of the previous published studies included in the meta-analysis which preclude broad conclusions—including challenges related to small sample sizes and insufficient power to detect small interaction effects, as well as wide heterogeneity across measures of ECE treatments and subsequent educational environments.

There is some evidence in support of dynamic complementarity. For example, Johnson and Jackson (2019) found that the long-term benefits of financial investments in the federal Head Start program were larger in the context of higher subsequent investments in public schooling. Other studies based on ECE treatment-control group designs also provide support for complementarity. These studies considered relevant measures of school-wide average academic achievement (Ansari & Pianta, 2018; Carr et al., 2021; Unterman & Weiland, 2020; Zhai et al., 2012) and school-wide growth in academic achievement (Carr et al., 2021; Pearman et al., 2020; Unterman & Weiland, 2020). One study in particular examined the effects of NC Pre-K program participation on child outcomes at the end of kindergarten and found that program effects on child language and working memory skills were only evident in higher-quality elementary schools—measured by school-wide academic proficiency and academic growth, respectively (Carr et al., 2021). However, this study did not find evidence of effects on child literacy and math outcomes.

Alternatively, several studies provide support for the dynamic substitutability hypothesis (Bierman et al., 2014; Curenton et al., 2015; Magnuson et al., 2007; Watts et al., under review). Most relevant to the current study, an ongoing study by our research team has examined school-wide average achievement as a moderator of the NC Pre-K funding effect on student achievement outcomes in fifth grade (Watts et al., under review). This study found that the positive effect of NC Pre-K funding was diminished in the context of elementary schools with lower-levels of school-wide average achievement. The current study extends these analyses in order to examine average achievement as well as achievement growth in relation to longer term outcomes in eighth grade.

The Current Study

The long-term effects of ECE may differ depending on the subsequent educational environments that children experience during school. However, the extant evidence is mixed regarding whether subsequent educational environments will play a role in moderating the long-term effects of ECE (Bailey, Jenkins, et al., 2020). The current study sought to address this issue by examining educational environments in NC public schools as moderators of the NC Pre-K program effect on student reading and math achievement in eighth grade. Building on our previous studies (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013) we examine variation in the rollout of NC Pre-K program funding allocated to NC's 100 counties across 18 program years in relation to student reading and math achievement in eighth grade.[6] We used a linked administrative dataset including more than one million children who were born in NC during an 18-year period.

In the first phase of our study, we used a growth curve model approach to measure educational environments in NC public school districts by (1) the average level of academic achievement among third-grade students in the school district and (2) the average rate of growth in academic achievement among students in the school district as they progressed from third to eighth grade. In the second phase of our study, we examined the effect of NC Pre-K program

[6] The current study extended the number of years of NC Pre-K program funding considered in the previous studies by six additional years to include 18 fiscal years of funding information. In doing so, we also increased the sample size by 299,580 students for the reading outcome analyses and 261,150 students for the math outcome analyses.

funding in relation to student reading and mathematics outcomes in eighth grade, and we simultaneously tested for moderation of the NC Pre-K program funding effect by the measures of the educational environment in NC public school districts. We considered three hypotheses. Support for the *complementarity* hypothesis would be evidenced by positive main effects of NC Pre-K program funding and school-district educational environment as well as a positive interaction between these inputs. Support for the *substitutability* hypothesis would be evidenced by positive main effects as well as a negative interaction between these inputs. Finally, support for the *additivity* hypothesis would be evidenced by positive mains effects, but no reliable interaction between these inputs.

Methods

Data Sources

Our study used data on the population of students enrolled in NC public schools in third grade through eighth grade between the 1996 and 2019 school years [7] (school records obtained from the NC DPI) as well as a subpopulation of these students who were also born in NC between January 1, 1987, and August 31, 2005 (birth records obtained from NC State Center for Health Statistics). Data on the full population of students were used in the Phase I analyses while data on the subpopulation of students were used in the Phase II analyses (described in further detail in the *Analyses* section below). To combine these data, the identified birth records and school records of individual students were matched by the NC Education Research Data Center (NCERDC) at Duke University. In the current study, 74% of all birth records were matched to a school record. We also utilized data on state allocations for NC Pre-K program funding obtained from the NC DPI, and publicly available data on each of NC's 100 counties obtained from the

[7] A school year is defined as July 1st of the previous year through June 30th of the listed year.

NC Office of State Budget and Management (OSBM). Institutional Review Board approval for this research was obtained at Duke University under the project titled "Combining Birth Data with Longitudinal Data on Schooling to Explore the Relationships Between Children's Birth Weight, Immigrant Status, Pre-School Experiences and Performance in School" (Protocol: 2017-0495). Some, but not all of the data and study materials are available through NCERDC (https://childandfamilypolicy.duke.edu/north-carolina-education-research-data/). The study analysis code can be made available from the corresponding author upon request. This study was not preregistered.

Measures

NC Pre-K funding exposure

Data on NC Pre-K program funding were obtained from the state administrative agency, which allocated funds to program contractors in local communities (i.e., counties) on a state fiscal year basis.[8] We converted all funds into 2019-dollar values based on the Consumer Price Index. To calculate county-level exposure to NC Pre-K funding, we divided the amount of NC Pre-K funds awarded to each county during each fiscal year by the number of age-eligible children (i.e., age 4) in each county during each fiscal year (based on county-level population estimates from NC OSBM):

$$NC\ Pre\ K\ funding\ exposure = \frac{NC\ Pre\ K\ funds\ in\ FY}{4\ year\ olds\ in\ FY}$$

Children were assigned to the value of county-level NC Pre-K funding exposure during the fiscal year in which they were 4 years old and eligible to benefit from the program. The NC Pre-K program was established during state fiscal year 2002. After the program was established,

[8] A total of 91 NC Pre-K program contractors served NC's 100 counties during each fiscal year. Funds awarded to a single contractor that served multiple counties were disaggregated across counties within the contractor's service region based on the population of age-eligible children in each county.

the average county-level exposure to NC Pre-K funding grew steadily and reached a peak of $2,030 in 2010, with considerable variation within and across counties over the study period (see Figure S1). The average county-level exposure to NC Pre-K funding between program years 2002-2010 was $1,064. We estimated that the program directly served 28% of all four-year-old children in NC in 2010 (the last year of program funding considered in the current study).

Student Achievement in Reading and Mathematics

Standardized assessments of reading and mathematics achievement were administered to students in NC public schools at the end of each grade between third grade and eighth grade. Our study used scores from these end-of-grade (EOG) tests administered during all school years between 1996 and 2019. These data were obtained from the NCERDC. The EOG tests are state-mandated, standardized assessments with well-documented psychometric characteristics that satisfy the requirements of the U.S. Department of Education (Bazemore & Van Dyk, 2004; Mbella et al., 2016a, 2016b; North Carolina Department of Public Instruction, 2009; Sanford, 1996). Separate editions of the EOG tests were administered across the range of years included in our panel study (i.e., four editions of the EOG Reading and five editions of the EOG Math). To account for changes in the scaling of EOG test editions across years, we converted the EOG scores into *Z*-scores (across all editions) by subject, school year, and grade level, resulting in a *Z*-score of 0.00 equal to the statewide average for students in each grade during each school year.

Covariates

Student covariates. Data on individual students were obtained from (a) the birth records data and (b) the school records data. The student covariates include student sex (Female = 0, Male = 1; school records); student economic disadvantage (No = 0, Yes = 1; school records); student birth weight categorized as extremely low, very low, low, normal (reference category), or high (birth records); student race categorized as non-Hispanic White (reference category), African American, Hispanic, Native American, Asian, or mixed race (school records); the quarter of the calendar year in which the child was born, categorized as quarter 1, 2, 3, and 4 (with quarter 3 as the reference category; adjusted for the kindergarten entry date and defined as the youngest children eligible for kindergarten entry during the school year; birth records); maternal education in years (birth records); parent marital status (Not married = 0, Married = 1; birth records); maternal age in years (birth records); no dad information on birth record (birth records); mother immigrant (No = 0, Yes = 1; birth records); student was first born (No = 0, Yes = 1; birth records); mother race categorized as non-Hispanic White (reference category), African American, Hispanic, Native American, Asian, or mixed race (birth records).

School-district covariates. Data on NC's public school districts across years were obtained from the NCERDC. The school-district covariates include the per pupil expenditures from local, state, and federal funding sources (converted to 2019 $s), the percent of economically disadvantaged students in the school district, and the total number of students in the school district's membership during eighth grade.[9]

County covariates. Socio-demographic data on each of NC's 100 counties across years were obtained from (a) the NC OSBM or (b) the birth records data aggregated from student-level information to county-level information. These county covariates include the percent of births to African American mothers, Hispanic mothers, and low education mothers (< 12 years of education) (birth records); the percent of population receiving Food Stamps and the percent of population receiving Medicaid (NC OSBM); the total number of births (log transformed; birth

[9] School-district economic disadvantage was measured based on the percent of students in the school district who qualified for free- or reduced-price lunch.

records); the total population (log transformed; NC OSBM); and median family income (converted to 2019 $s; NC OSBM).

Data on Smart Start program funding were obtained from the NC Partnership for Children. The Smart Start program was established in 1993 by the NC General Assembly to serve children (and their families) from birth to age 5 in three main areas: child care subsidy and quality improvement, family support services, and child health/wellbeing. The NC Partnership for Children awards funds to local Smart Start partnerships to provide program services in each of NC's 100 counties. Local decision-making is a hallmark of the Smart Start program, as the activities of local partnerships in each of NC's 100 counties are guided by a board of community members who select the services that best meet the needs of children and families in their community (North Carolina Partnership for Children, 2019). The decentralized nature of the Smart Start program leads to varied implementation of program services across counties and over time. Therefore, the implemented program can best be described as a pool of financial resources with guidelines for spending. In the current study, we control for children's exposure to Smart Start funding. Smart Start funds were allocated to program contractors/counties on a state fiscal year basis (converted to 2019 $s).[10] To calculate county-level exposure to Smart Start funding, we first divided the amount of Smart Start funds awarded to each county during each fiscal year by the number of age-eligible children (i.e., birth to age 5) in each county during each fiscal year (based on county-level population estimates from NC OSBM).[11] We then summed the annual Smart Start funding exposure in each county across each five-year fiscal year period in which children in our panel were eligible to benefit from the program (i.e., between birth–age 1,

[10] The NC Partnership for Children provided Smart Start funding data expended by program contractors in each of NC's 100 counties during each fiscal year.

[11] The Smart Start and NC Pre-K funding exposure variables were based on the entire population of age-eligible children even if only a portion of children received direct financial support to participate in the program.

age 1–2, age 2–3, age 3–4, and age 4–5). Children were assigned to the value of county-level Smart Start funding exposure during the five-year fiscal year period in which they were eligible to benefit from the program.

Analyses

Analyses proceeded in two phases. In the first phase, we measured school-district average achievement in third grade and achievement growth from third to eighth grade among students in NC public school districts. We then examined correlates of average achievement and achievement growth. In the second phase of analysis, we examined the main effects of NC Pre-K program funding exposure as well as school-district average achievement and achievement growth in relation to student achievement outcomes in eighth grade, and we simultaneously examined interactions between NC Pre-K program funding exposure and each measure of the subsequent educational environment. All analyses were completed in SAS® version 9.4.

Phase I: Measuring School-District Average Achievement and Achievement Growth

In Phase I of our analyses, we measured school-district average achievement and achievement growth for 18 cohorts of students who progressed from third to eighth grade in each of NC's 115 public school districts (see Figure S3).[12,13,14] We began with third grade because it was the lowest grade level at which standardized achievement tests were administered in NC. We used the reading and math scores drawn from the full population of students enrolled in NC

[12] We note that 4 public school districts were closed and consolidated with other public-school districts during the course of our panel years. For our study, we aggregated information within these consolidated school districts prior to the years in which they were consolidated to utilize 115 school districts across all study years.
[13] All charter school districts were excluded from our study. The following public-school districts were also excluded from our study because they were not comparable to the 115 traditional public-school districts: (1) the NC Schools for the Blind and Deaf and (2) the NC School of Science and Mathematics.
[14] There are 75 counties in NC that were served by a single school district, while 15 counties were served by two school districts.

public schools with valid EOG test score data.[15] The growth cohorts were defined as all students who took the third grade through eighth grade reading and/or math assessments during a six-year period.[16,17] For example, the first growth cohort was defined by all students who took the third-grade reading and/or math assessment in 1996, the fourth-grade assessment in 1997, the fifth-grade assessment in 1998, the sixth-grade assessment in 1999, the seventh-grade assessment in 2000, and/or the eighth-grade assessment in 2001.

We estimated a multi-level growth curve model for each of the 18 growth cohorts, with separate models estimated for reading and math scores (18 × 2 = 36 models total). All models were estimated using the HPMIXED procedure in SAS® version 9.4. The generalized equation for the multi-level growth curve models to measure school-district average achievement and achievement growth is shown below (with separate models calculated for each of the 19 cohorts):

Level-1 (time; *t*):

$$Y_{tij} = \pi_{0ij} + \pi_{1ij} time_{tij} + e_{tij}$$

Level-2 (students; *i*):

$$\pi_{0ij} = \beta_{00j} + r_{0ij}$$
$$\pi_{1ij} = \beta_{10j} + r_{1ij}$$

Level-3 (school districts; *j*):

$$\beta_{00j} = \gamma_{000} + u_{00j}$$
$$\beta_{10j} = \gamma_{100} + u_{10j}$$

[15] The following categories of students were excluded from our analyses because they took alternative assessments with test scales that were not equated with the EOG scale: (a) students with disabilities who took alternative assessments specifically designed to meet their needs and (b) advanced eighth grade students who were not assessed with the EOG Math test in 2019, but were instead assessed using the high-school end-of-course (EOC) math test (1.6% of our input sample).
[16] The scores of individual students who were retained in grade and had valid test scores recorded for the same grade assessment in separate years were included in the models for multiple cohorts (e.g., the scores for a student who took the third-grade assessment during the 1997 and 1998 school years were included in the models for cohorts 2 and 3, respectively).
[17] Within cohorts, the scores of students who changed school districts were included in each respective school district (e.g., the scores for a student who took the third- through fifth-grade assessments in school district A were nested within school district A, and the scores for that same student who took the six- through eighth-grade assessments in school district B were nested within school district B).

Variance Components:

$$e_{tij} \sim N(0, \sigma_{tij})$$
$$r_{0ij} \sim N(0, \sigma_{0ij})$$
$$r_{1ij} \sim N(0, \sigma_{1ij})$$
$$u_{00j} \sim N(0, \sigma_{00j})$$
$$u_{10j} \sim N(0, \sigma_{10j})$$

$\boldsymbol{Y_{tij}}$ is the test score at time *t* (grade) for student *i* in school district *j*; $time_{tij}$ is coded as 0 at third grade, 1 at fourth grade, 2 at fifth grade, 3 at sixth grade, 4 at seventh grade, and 5 at eighth grade (separate models were calculated for reading and mathematics scores)

$\boldsymbol{\pi_{0ij}}$ is the expected achievement level (i.e., intercept) for student *i* in school district *j* in third grade

$\boldsymbol{\pi_{1ij}}$ is the expected achievement growth (i.e., linear slope) for student *i* in school district *j* during each grade between third and eighth grade

$\boldsymbol{\beta_{00j}}$ is the expected achievement level (i.e., intercept) for students in school district *j* in third grade

$\boldsymbol{\beta_{10j}}$ is the expected achievement growth (i.e., linear slope) for students in school district *j* during each grade between third and eighth grade

In this model, repeated assessments of students' reading or mathematics skills over time (*t*; Level-1) were nested within students (*i*; Level-2), and students were nested within school districts (*j*; Level-3). Time was coded as 0 at third grade, 1 at fourth grade, 2 at fifth grade, 3 at sixth grade, 4 at seventh grade, and 5 at eighth grade. Test scores (Y_{tij}) were modeled as a function of (1) an intercept term centered at the third-grade assessment score to represent the expected achievement level for student *i* in school district *j* in third grade (π_{0ij}) and the expected achievement level for students in school district *j* in third grade (β_{00j}) as well as (2) a linear slope term to represent the expected achievement growth for student *i* in school district *j* during each grade between third and eighth grade (π_{1ij}) and the expected achievement growth for students in school district *j* during each grade between third and eighth grade (β_{10j}). The intercept term was allowed to vary randomly between students (r_{0ij}) and school districts (u_{00j}), and the slope term was also allowed to vary randomly between students (r_{1ij}) and school districts

(u_{10j}). All of the variance terms were parameterized to be normally distributed random variables with a mean of zero. We specified an unstructured covariance matrix to allow the random intercepts and slopes and their variances to be correlated with one another at Level-2 and at Level-3 in order to allow for a systematic relation between intercepts and slopes. We used restricted maximum likelihood (REML) to estimate the variance components and the “residual” method to calculate denominator degrees of freedom. Students with at least one test score were included in these analyses and maximum likelihood was used to account for missing data (Singer & Willett, 2003). No covariates were included in these analyses in order to calculate unconditional estimates of the intercepts and slopes.

Based on the results of this model, we derived estimates of average achievement (i.e., intercept; β_{00j}) and achievement growth (i.e., slope; β_{10j}) in reading/math for each of the 115 school-districts across the 18 cohorts for use in the subsequent analyses. Specifically, we derived the empirical best linear unbiased predictions (EBLUPs) for the realizations of the random intercept, slope, and nested errors. This model was conceptually similar to model 8.15–8.17 described by Bryk and Raudenbush (1992). Based on the results of these analyses, we examined correlations between school-district economic disadvantage, average achievement, and achievement growth in order to better understand the validity of these measures.

Phase II: Eighth-Grade Student Achievement Analyses

In Phase II of our analyses, we examined the effect of NC Pre-K program funding exposure on student reading and math achievement outcomes in eighth grade as well as moderation of the NC Pre-K effect by school-district average achievement and achievement growth. Using two-way fixed effect linear regression analyses, we estimated the effect of NC Pre-K program funding as the weighted average of between-county effects and within-county effects across time—weighted by variance and sample size (Kropko & Kubinec, 2020). A generalized equation is shown below for the two-way fixed effect analyses to examine the effect of NC Pre-K funding exposure on students' eighth grade outcomes and moderation by school-district average achievement and achievement growth:

$$O_{iscByPySy} = \beta_0 + \beta_1 NCPK\ funding_{cPy} + \beta_2 Avg\ Ach_{sSy-1} + \beta_3 Ach\ Growth_{sSy-1}$$
$$+\beta_4 NCPK\ funding\ x\ Avg\ Ach_{scPySy-1} + \beta_5 NCPK\ funding\ x\ Ach\ Growth_{scPySy-1}$$
$$+ \boldsymbol{X}_i + \boldsymbol{Z}_{sSy} + \boldsymbol{C}_{cBy} + \alpha_{cBy} + \gamma_{iPy} + (\alpha * \gamma)_{icByPy} + \epsilon_{iscByPySy}$$

In this model, O is the eighth-grade test score (with separate models estimated for reading and mathematics scores) for student *i*, enrolled in eighth grade in school district *s*, born in county *c*, born in birth year *By*, exposed to program funding during program year *Py*, and enrolled in eighth grade during school year *Sy*;[18] β_1 is the main effect of NC Pre-K funding exposure;[19] β_2 is the main effect of school-district average achievement (i.e., average achievement in reading for the reading outcome model and average achievement in math for the math outcome model); β_3 is the main effect of school-district achievement growth (i.e., achievement growth in reading for the reading outcome model and achievement growth in math for the math outcome model); β_4 is the interaction between NC-Pre-K funding exposure and school-district average achievement; β_5 is the interaction between NC-Pre-K funding exposure and school-district achievement growth; X is a vector of effects for the student-level covariates; Z is a vector of effects for the school-district-level covariates; C is a vector of effects for the county-level covariates; α is the fixed effect for county of residence to account for within-county variation in program funding over

[18] For students who repeated eighth grade, we used the test score that was recorded during the first school year in which they were enrolled in eighth grade.

[19] In a two-way fixed effect analysis with a continuous treatment, a key assumption of the treatment effect estimand concerns the linearity of the treatment effect (i.e., if the treatment effect is non-linear, then the two-way fixed effect estimand may differ meaningfully from the average causal response parameter; Callaway et al., 2021). We tested for evidence of non-linearity by estimating a quadratic (i.e., non-linear) effect of NC Pre-K funding exposure in our models and we did not find reliable evidence of non-linearity (p = .37–.99).

time; γ is the fixed effect for program year to account for between-county variation in program funding; $\alpha * \gamma$ is the linear time trend for each county across program years to account for trends in student achievement outcomes among students born within counties over time (for more details, see Dynarski et al., 2018); and ϵ is the residual term.[20] All models were estimated with robust standard errors clustered at the county level.

The program funding, county-level covariates, and county fixed effect were aligned to students' county of residence and year of birth.[21] The school-district covariates were aligned to the students' school district and school year during eighth grade. The school-district average achievement and achievement growth measures were aligned to the students' school district during eighth grade, and we implemented a "current year minus 1" approach to assign values to students in a given school year on the basis of values derived from the prior school year, with a different set of students (e.g., students enrolled in eighth grade in 2002 were assigned school-district average achievement and achievement growth values from cohort #1, which was comprised of students enrolled in eighth grade in 2001, and so on).[22] This approach was similar to that used by Andrabi et al. (2011).

The NC Pre-K funding exposure variable was scaled such that a 1-unit change was equal to a change from $0 to $2,030 (i.e., during our study period, the average county-level exposure to NC Pre-K funding reached a peak of $2,030 in 2010; see Figure S1). The dependent variables

[20] We conducted a series of endogeneity analyses to examine the association between NC Pre-K program funding exposure and school-district average achievement & achievement growth (see Table S4). We found no reliable association between NC Pre-K funding and school district average achievement or achievement growth in reading and math. These findings suggest that our analyses satisfy a necessary condition to examine moderation.

[21] In previous studies, we have found the pattern of findings remained the same between analyses based on county of residence at birth and county of school attendance (Bai et al., 2020).

[22] This approach was employed in order to avoid the confound using student test score information from the same students as both independent and dependent variables, because regressing student's eighth grade achievement scores on school-district average achievement and achievement growth values measured from the same student test scores could introduce the same estimation errors on both the left- and right-hand side of the regression equation—resulting in biased estimates for school-district average achievement and achievement growth.

and continuous independent variables were grand mean standardized for the analysis sample with $M = 0$, $SD = 1$ (with separate standardization conducted for the reading and math outcome analysis samples). Dichotomous independent variables were centered, but not standardized (with separate centering conducted for the reading and math outcome analysis samples). As a result of grand mean standardizing the school-district average achievement and achievement growth measures, the main effect of NC Pre-K funding exposure can be interpreted in the context of the interaction terms at the average level of school-district average achievement and achievement growth. All models were estimated using the SURVEYREG procedure in SAS® version 9.4. These analyses relied on the subsample of students in NC public schools with birth records matched to school records. From this matched subsample, only 7% and 10% of students had missing data on one or more study variables for the reading and math outcome analyses, respectively, and we applied listwise deletion to these cases.

Results

Phase I: Measuring School-District Average Achievement and Achievement Growth

We measured school-district average achievement and achievement growth in reading and mathematics for 18 cohorts of students who progressed from third to eighth grade between 1996 and 2018. Based on EOG scores transformed to *Z*-scores, we found that school-district average achievement in third grade was –0.13 ($SD = 0.22$) for reading and –0.14 ($SD = 0.23$) for math (see Table S1). These findings indicated that the average third grade achievement of students in the public school districts in our sample was slightly more than one tenth of a standard deviation below the statewide average.[23] Based on EOG scores transformed to *Z*-scores,

[23] Please note that a student-level reading and math *Z*-score value of 0.00 indicates the statewide average for all students in NC public school districts during each school year. The negative mean values for school-district average achievement displayed here imply (a) the clustering of lower performing students in districts as well as (b) the exclusion of some students from our analyses sample, because all test takers were included in the transformation of

we found that school-district achievement growth from third to eighth grade was –0.02 points (*SD* = 0.20) for reading and –0.01 points (*SD* = 0.20) for math.[24] These findings indicated that, on average, students in the public school districts in our sample showed only negligible declines in their statewide rank-order standing in *Z*-scores between third and eighth grade.

We examined correlates of school-district average achievement and achievement growth (see Table S2). First, we found that school-district average achievement and achievement growth were weakly correlated for both reading ($r = 0.04$, $p = .04$) and math ($r = –0.16$, $p < .001$). These findings suggest that average achievement and achievement growth may reflect distinct dimensions of educational environments in North Carolina public school districts. Second, we found that average achievement in reading was highly positively correlated with average achievement in math ($r = 0.92$, $p < .001$) and achievement growth in reading was highly correlated with achievement growth in math ($r = 0.66$, $p < .001$). These findings offer some evidence of convergent validity for each measure of the educational environment. Third, we found that school-district economic disadvantage was highly negatively correlated with average achievement in reading ($r = –0.65$, $p < .001$) and math ($r = –0.65$, $p < .001$). Alternatively, we found that school-district economic disadvantage showed a weak negative correlation with achievement growth in reading ($r = –0.19$, $p < .001$) and math ($r = –0.07$, $p = .002$). Consistent

EOG scale scores to *Z*-scores, but some students were excluded from Phase I and II analyses (e.g., students in charter school districts).

[24] The original values for school-district achievement growth represented a single grade/year of growth. These yearly values were rescaled to represent the linear rate of growth from third to eighth grade by multiplying the grade/year rate of growth produced in the Phase I analyses by a value of 5. The interpretation for a school-district achievement growth score of 0.00 is that the school district's rank-order standing remained at the statewide average from third to eighth grade. The interpretation for a positive school-district achievement growth score is that the school district gained in rank-order standing among all public-school districts from third to eighth grade, while the interpretation for a negative school-district achievement growth score is that the school district declined in rank-order standing among all public-school districts from third to eighth grade.

with Reardon (2019), our findings suggest that average achievement may reflect a broad range of socioeconomic conditions of the community where the school district is located, while achievement growth may better reflect the unique contributions of schooling toward promoting student achievement during the elementary and middle school grades.

Phase II: Eighth-Grade Student Achievement Analyses

Tables 1 and S3 summarize the descriptive information on all study variables at the student level. Table 2 summarizes the results of regression analyses to examine the effects of NC Pre-K funding exposure on students' eighth grade reading and math achievement, as well as moderation of the NC Pre-K effect by the subsequent educational environment in NC public school districts.

Reading. We found positive main effects of NC Pre-K funding exposure ($\beta = 0.07$, $p = .003$), school-district average achievement in reading ($\beta = 0.04$, $p < .001$), and school-district achievement growth in reading ($\beta = 0.03$, $p < .001$) in relation to student's eighth grade reading achievement.[25] The effect of NC Pre-K funding exposure was not reliably moderated by school-district average achievement ($\beta = –0.01$, $p = .14$). However, we found that the effect of NC Pre-K funding exposure was moderated by school-district achievement growth such that the magnitude of the NC Pre-K effect decreased as achievement growth increased ($\beta = –0.02$, $p < .001$). When we probed the interaction, we found the NC Pre-K effect was positive at each level of achievement growth but became smaller as achievement growth increased from *low* levels (i.e., 1 *SD* below the average; $\beta = 0.09$, $p < .001$) to *average* ($\beta = 0.07$, $p = 0.003$) and then *high* levels (i.e., 1 *SD* above the average; $\beta = 0.04$, $p = 0.07$) (see Figure 1).

[25] We found that the positive main effect of NC Pre-K funding exposure was evident in relation to student's eighth grade reading achievement when school-district average achievement and achievement growth in reading were excluded from the analyses ($\beta = 0.08$, $p < .001$; see Table S5).

Math. We found positive main effects of NC Pre-K funding exposure ($\beta = 0.09$, $p = .03$), school-district average achievement in math ($\beta = 0.07$, $p < .001$), and school-district achievement growth in math ($\beta = 0.08$, $p < .001$) in relation to student's eighth grade math achievement.[26] The effect of NC Pre-K funding exposure was not reliably moderated by school-district average achievement ($\beta = –0.01$, $p = .53$). However, we found that the effect of NC Pre-K funding exposure was moderated by school-district achievement growth such that the magnitude of the NC Pre-K effect decreased as achievement growth increased ($\beta = –0.03$, $p = .007$). When we probed the interaction, we found the NC Pre-K effect was positive at each level of achievement growth but became smaller as achievement growth increased from *low* levels ($\beta = 0.11$, $p = .003$) to *average* ($\beta = 0.09$, $p = 0.03$) and then *high* levels ($\beta = 0.06$ $p = 0.15$).

Discussion

High-quality ECE can have positive effects on student achievement outcomes. What remains unclear is whether the subsequent educational environments students experience during school will enhance or diminish the long-term effects of ECE (Bailey, Jenkins, et al., 2020). Building on our previous studies, we examined the effect of NC Pre-K program funding in relation to student reading and math achievement in eighth grade (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013; Muschkin et al., 2015). The unique contribution of our study was to examine the interaction between NC Pre-K funding and two key dimensions of the subsequent educational environment students experience during school: average achievement and achievement growth. We considered three hypotheses regarding the role that subsequent

[26] We found that the positive main effect of NC Pre-K funding exposure was evident in relation to student's eighth grade math achievement when school-district average achievement and achievement growth in math were excluded from the analyses ($\beta = 0.11$, $p = .01$; see Table S5).

educational environments might play in interacting with the long-term effects of NC Pre-K—*complementarity*, *substitutability*, and *additivity*.

In relation to student reading and math achievement in eighth grade, the interaction between NC Pre-K funding exposure and average achievement showed support for the additivity hypothesis, while the interaction between NC Pre-K funding exposure and achievement growth showed support for the substitutability hypothesis. In support of the additivity hypothesis, we found no reliable interaction between NC Pre-K funding exposure and school-district average achievement—suggesting that increases in NC Pre-K funding exposure during preschool continued to exert a positive effect on student reading and math achievement in eighth grade, but that effect was neither enhanced nor diminished by the level of average academic achievement in the school district. In other words, investments in NC Pre-K continued to benefit children in the long run, regardless of whether they went on to attend school districts with higher or lower levels of average academic achievement. At the same time, attending a school district with higher levels of average achievement also led children to attain higher levels of reading and math achievement in eighth grade. These findings suggest that ECE and subsequent educational inputs contributed to eighth grade reading and math outcomes in a main-effect, additive way.

In support of the substitutability hypothesis, we found a negative interaction between NC Pre-K funding exposure and school-district achievement growth—suggesting that the positive effect of NC Pre-K funding was larger in school districts with lower rates of growth in academic achievement. In this way, higher exposure to NC Pre-K funding during preschool appeared to buffer children against the consequences of subsequently enrolling in a lower-growth school district. This was the case because the academic achievement scores of students in lower-growth school districts most closely approximated the scores of students in higher-growth school districts if they were also exposed to higher-levels of NC Pre-K program funding (see Figure 1). Simultaneously, the developmental benefit of higher-growth school districts appeared to act as a substitute for children with low *or* no exposure to NC Pre-K during early childhood.

Substitutability by achievement growth could be evident for NC Pre-K because the program has long maintained a focus on promoting children's school readiness skills, including frequent and high-quality instruction related to early academic skills (e.g., Peisner-Feinberg et al., 2013). Hence, the developmental benefits resulting from higher exposure to NC Pre-K may have buffered students from the consequences of enrolling in a school district with lower rates of growth in academic achievement. Alternatively, enrolling in a school district with higher rates of growth in academic achievement may have enabled students with low or no exposure to NC Pre-K to make up the gains in underlying reading and math skills that NC Pre-K would have otherwise conferred. In sum, the benefits conferred through NC Pre-K as a school readiness skill-building intervention can be maintained in the long run, and these benefits might be most pronounced for students who go on to enroll in school districts where growth in academic skill development is lower.

Our study focused on the educational environments in school districts as the unit of analysis. We found that school-district average achievement and achievement growth both had positive main effects on student reading and math achievement in eighth grade. However, it is important to note that average achievement—but not achievement growth—showed a strong, negative correlation with the level of socioeconomic disadvantage among students in the school districts. This suggests that average achievement might measure the wide range of educational inputs available to students in their communities. Alternatively, achievement growth might better reflect the unique contributions of schooling toward promoting student skill development.

Therefore, these different dimensions of the educational environment during school can represent different pathways toward raising student achievement. For example, the benefits of enrolling in a school district with higher levels of average student achievement may begin to accrue as soon as children step inside the kindergarten door—impacting early skill attainment—while the benefits of achievement growth may require multiple years of exposure in order to accrue benefits—impacting later skill attainment. Additionally, the educational benefits of enrolling in a school district with higher levels of average achievement may extend beyond the experiences students have during the school day to their experiences in community centers and after school programs. An ongoing study by our research team has found that the positive effect of NC Pre-K funding on student achievement outcomes in fifth grade was diminished in the context of elementary schools with lower-levels of school-wide average achievement (Watts et al., under review). However, that study was not able to examine achievement growth (in addition to average achievement) in relation to student achievement outcomes and it focused on medium-term outcomes in fifth grade. A unique contribute of the current study points to achievement growth—rather than average achievement—as an important factor in differentiating the long-term benefits of NC Pre-K through eighth grade.

Finally, we found main effects of NC Pre-K funding exposure in the current study that may be considered small by conventional standards (e.g., a difference of $2,030 in NC Pre-K funding exposure led to a 0.07 and 0.09 *SD* unit increase in eighth grade reading and math achievement, respectively). However, these small magnitude effects were educationally meaningful according to empirical benchmarks established for educational interventions (Kraft, 2020). These effects can be further contextualized by the moderate cost (i.e., not small or large; Kraft, 2020) of NC Pre-K funding exposure: $2,030 was the average amount of NC Pre-K funding allocated per 4-year-old children in North Carolina during the most recent program year considered in our study (i.e., 2009-10) and this funding level has remained relatively stable since then. Overall, the reasonable cost of investments in NC Pre-K programming produced population-wide improvements in student achievement outcomes that remained educationally meaningful in the long-term—suggesting that even larger investments could produce greater impact in the future.

In the debate concerning persistence in the long-term effects of ECE on student achievement, the findings of our research should encourage educational stakeholders and policymakers to be mindful of the role that subsequent schooling environments can play in determining whether ECE program effects are maintained or diminished in the long run. While our previous studies have documented NC Pre-K's enduring effects on academic achievement outcomes through elementary school and middle school (Bai et al., 2020; Dodge et al., 2016; Ladd et al., 2013), findings from the current study point out the possible conditional nature of these effects. We found that the average rate of academic achievement growth in the school district made a difference in determining whether ECE program effects on student achievement were enhanced or diminished in the long run. Historically, exposure to NC Pre-K might have had the largest long-term effect for students who went on to enroll in school districts where growth in academic achievement was lowest. Today, efforts to expand access to NC Pre-K programming have become a policy priority in North Carolina (Carr & Peisner-Feinberg, 2021, September 13). If access to NC Pre-K programming becomes more readily available in the future, educators and policymakers might seek to promote greater continuity in high-quality educational environments across preschool and school. Several frameworks have been developed to promote educational alignment (e.g., Kauerz & Coffman, 2013). Consistent with these alignment frameworks, we advocate for a view of NC Pre-K programming and its benefits as part of a continuum of high-quality educational inputs to be built upon sequentially across development (Carr, 2021).

Study Limitations

The current study focused on educational environments in school districts as the unit of analysis, and our measures of average achievement and achievement growth were both positively associated with student achievement in eighth grade. Nonetheless, it is possible that educational environments may vary between schools within school districts. However, this consideration was outside the scope of our study because many schools did not include the full range of grade levels needed to measure average achievement and achievement growth from third to eighth grade. Additionally, we did not examine moderation of the NC Pre-K effect on student outcomes in earlier grades, because school-district average achievement and achievement growth entailed the measurement of student achievement between third and eighth grade—confounding earlier grade outcomes with information from eighth grade academic achievement.

Conclusion

Our study adds important nuance to a body of evidence documenting the positive, long-term effects of North Carolina's NC Pre-K program. While our prior research has shown that financial investments in NC Pre-K can have population-wide effects on student reading and math achievement that endure through the end of middle school—nine years after program exposure—the current study contributes new evidence regarding the role of school-age educational environments in differentiating these long-term effects. Specifically, we found that the positive effect of financial investments in NC Pre-K was larger for students who subsequently enrolled in school districts with lower rates of growth in academic achievement on average. These findings provide support for the dynamic substitutability hypothesis, which suggests that ECE effects will be most effective in the long term in the context of lower-quality educational environments during school. In the debate about the persistence (or not) of ECE program effects on student achievement, we encourage educational stakeholders and policymakers to consider the role that subsequent schooling environments can play a role in determining how ECE effects are maintained or diminished in the long run.

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Table 1

Descriptive Statistics for the Eighth Grade Student Reading Achievement Analysis Sample (N = 1,160,725)

Variable	*M*	(*SD*)
NC Pre-K program funding		
NC Pre-K funding exposure (in 2019 $s; all study years)	420	(671)
Eighth grade achievement outcomes		
Reading	-0.01	(1.00)
Math	0.00	(1.00)
School-district average achievement		
Reading	-0.09	(0.18)
Math	-0.10	(0.19)
School-district achievement growth		
Reading	-0.02	(0.10)
Math	0.00	(0.16)
Student covariates		
Sex (Male; %)	50	
Economic disadvantage (%)	46	
Extremely low birth weight (%)	<1	
Very low birth weight (%)	1	
Low birth weight (%)	7	
Normal birth weight (%)	82	
High birth weight (%)	10	
Non-Hispanic White (%)	58	
African American (%)	30	
Hispanic (%)	7	
Native American (%)	1	
Asian (%)	2	
Mixed race (%)	3	
Quarter of birth 1 (%)	25	
Quarter of birth 2 (%)	25	
Quarter of birth 3 (%)	30	
Quarter of birth 4 (%)	21	

Table 1 (continued)

Descriptive Statistics for the Eighth Grade Student Reading Achievement Analysis Sample (N = 1,160,725)

Variable	*M*	(*SD*)
Maternal education (years)	12.58	(2.55)
Parent marital status (%)	65	
Maternal age (years)	26.11	(5.93)
No dad information on birth record (%)	14	
Mother immigrant (%)	9	
First born (%)	43	
Mother Non-Hispanic White (%)	60	
Mother African American (%)	29	
Mother Hispanic (%)	7	
Mother Native American (%)	2	
Mother Asian (%)	1	
Mother mixed race (%)	<1	
School-district covariates		
Total per pupil expenditures (in 2019 $s)	9822	(977)
Economic disadvantage (% in school district)	52.05	(15.76)
School district membership	39685	(45559)
County covariates		
Births to African American mothers (% of births)	25.74	(14.47)
Births to Hispanic mothers (% of births)	7.97	(11.07)
Births to low education mothers (% of births)	22.59	(6.56)
Population on Food Stamps (% of population)	7.41	(3.64)
Population on Medicaid (% of population)	14.42	(5.89)
Number of births (log transformed)	7.51	(1.09)
Total population (log transformed)	11.77	(1.00)
Median family income (in 2019 $s)	68309	(13232)
Smart Start funding exposure (in 2019 $s; all study years)	1462	(1088)

Note. Descriptive statistics are provided for those students included in the reading outcome analyses. Descriptive statistics for students included in the math outcome analyses are provided in Table S3. Dollar amounts for NC Pre-K funding exposure, total per pupil expenditures, median family income, and Smart Start funding exposure variables were scaled to raw dollar amounts in fiscal year 2019 $s, with all study years represented (including pre-trend years in which NC Pre-K funding exposure was equal to 0 for students in all counties). School-district average achievement in reading/math was measured at third grade and achievement growth in reading/math was measured from third to eighth grade. All values of school-district average achievement and achievement growth were “current year minus 1.”

Table 2

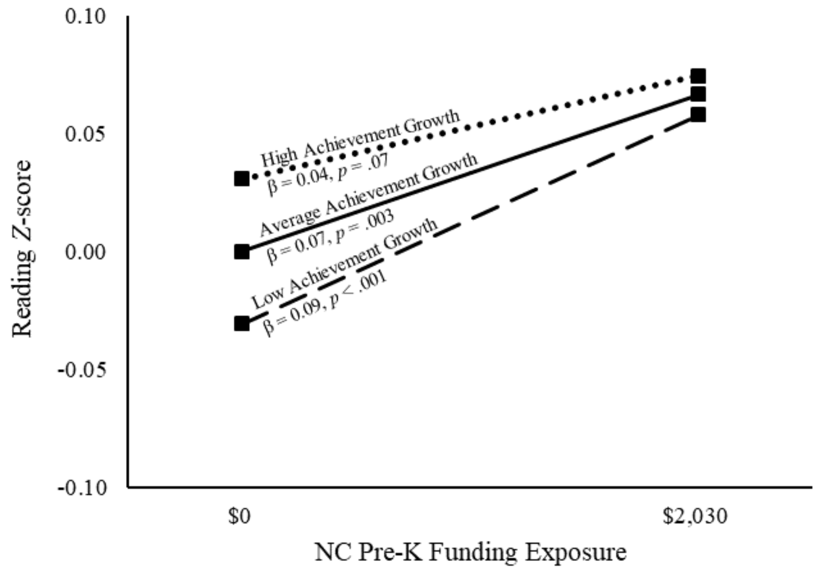
Eighth-Grade Student Achievement Analysis Results

	Reading		Math	
	N = 1,160,725		N = 1,123,347	
Parameter	β	(*SE*)	β	(*SE*)
NC Pre-K funding exposure	0.07**	(0.02)	0.09*	(0.04)
Average Achievement	0.04***	(0.01)	0.07***	(0.01)
Achievement Growth	0.03***	(0.00)	0.08***	(0.00)
NC Pre-K × Average Achievement	–0.01	(0.01)	–0.01	(0.01)
NC Pre-K × Achievement Growth	–0.02***	(0.01)	–0.03**	(0.01)
Covariates	Inc.		Inc.	
County fixed effects	Inc.		Inc.	
Program year fixed effects	Inc.		Inc.	
Linear time trends	Inc.		Inc.	
R-squared	0.27		0.27	

Note. Parameter estimates for the student, school-district, and county covariates; county fixed effects; program year fixed effects; and linear time trends are not displayed in Table 2, but can be made available from the corresponding author upon request. School-district average achievement/achievement growth correspond to reading average achievement/achievement growth in the reading models and math average achievement/achievement growth in the math models. All values of school-district average achievement and achievement growth were "current year minus 1." The effect of NC Pre-K funding exposure is equal to a change from \$0 to \$2,030. Eighth grade reading and math achievement as well as school district average achievement and achievement growth were grand mean standardized with $M = 0$, $SD = 1$. All models were estimated with robust standard errors clustered at the county level. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Figure 1

Moderation of the NC Pre-K Funding Effect on Eighth Grade Student Reading Achievement by School-District Achievement Growth in Reading



Note. The effect of NC Pre-K funding exposure on student reading achievement in eighth grade at three values of school-district achievement growth in reading: 1 *SD* below the average (low), at the average, and 1 *SD* above the average (high).

Online Supplementary Files

Table S1

Descriptive Statistics for School-District Average Achievement and Achievement Growth Presented at the School-District Level (N = 2,070)

Variable	*M*	(*SD*)
School-district average achievement		
Reading	–0.13	(0.22)
Math	–0.14	(0.23)
School-district achievement growth		
Reading	–0.02	(0.12)
Math	–0.01	(0.20)

Note. School-district average achievement in reading/math (β_{00j}) was measured at third grade and achievement growth in reading/math (β_{10j}) was measured from third to eighth grade. Economic disadvantage was measured based on the percent of students in the school district who qualified for free- or reduced-price lunch. There were 115 school districts in each of the 18 cohorts (i.e., 18 × 15 = 2,070 school district by cohort observations).

Table S2

Correlates of School-District Average Achievement & Achievement Growth (N = 2,070)

	1	2	3	4	5
School-district average achievement					
1. Reading	1.00				
2. Math	0.92^{***}	1.00			
School-district achievement growth					
3. Reading	0.04^{*}	$0.04^{\dagger}$	1.00		
4. Math	0.03	$–0.16^{***}$	0.66^{***}	1.00	
Economic Disadvantage					
5. Economic disadvantage (%)	$–0.65^{***}$	$–0.65^{***}$	$–0.19^{***}$	$–0.07^{**}$	1.00

Note. Economic disadvantage is the percent of economically disadvantaged students in the school district (i.e., the percent of students in the school district who qualified for free- or reduced-price lunch). $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Table S3

Descriptive Statistics for the Eighth Grade Student Math Achievement Analysis Sample (N = 1,123,347)

Variable	*M*	(*SD*)
NC Pre-K program funding		
NC Pre-K funding exposure (in 2019 $s; all study years)	385	(640)
Eighth grade achievement outcomes		
Reading	-0.04	(1.00)
Math	0.00	(1.00)
School-district average achievement		
Reading	-0.09	(0.18)
Math	-0.10	(0.19)
School-district achievement growth		
Reading	-0.02	(0.10)
Math	-0.01	(0.16)
Student covariates		
Sex (Male; %)	50	
Economic disadvantage (%)	47	
Extremely low birth weight (%)	<1	
Very low birth weight (%)	1	
Low birth weight (%)	7	
Normal birth weight (%)	82	
High birth weight (%)	10	
Non-Hispanic White (%)	58	
African American (%)	30	
Hispanic (%)	7	
Native American (%)	1	
Asian (%)	2	
Mixed race (%)	3	
Quarter of birth 1 (%)	24	
Quarter of birth 2 (%)	25	
Quarter of birth 3 (%)	30	
Quarter of birth 4 (%)	21	

Table S3 (continued)

Descriptive Statistics for the Eighth Grade Student Math Achievement Analysis Sample (N = 1,123,347)

Variable	*M*	(*SD*)
Maternal education (years)	12.53	(2.53)
Parent marital status (%)	65	
Maternal age (years)	26.01	(5.91)
No dad information on birth record (%)	14	
Mother immigrant (%)	9	
First born (%)	43	
Mother Non-Hispanic White (%)	61	
Mother African American (%)	29	
Mother Hispanic (%)	7	
Mother Native American (%)	2	
Mother Asian (%)	1	
Mother mixed race (%)	<1	
School-district covariates		
Total per pupil expenditures (in 2019 $s)	9817	(979)
Economic disadvantage (% in school district)	51.93	(15.64)
School district membership	38871	(44675)
County covariates		
Births to African American mothers (% of births)	25.84	(14.54)
Births to Hispanic mothers (% of births)	7.71	(11.12)
Births to low education mothers (% of births)	22.60	(6.58)
Population on Food Stamps (% of population)	7.39	(3.65)
Population on Medicaid (% of population)	14.35	(5.89)
Number of births (log transformed)	7.49	(1.08)
Total population (log transformed)	11.75	(1.00)
Median family income (in 2019 $s)	68018	(13141)
Smart Start funding exposure (in 2019 $s; all study years)	1452	(1103)

Note. Descriptive statistics are provided for those students included in the math outcome analyses. Dollar amounts for NC Pre-K funding exposure, total per pupil expenditures, median family income, and Smart Start funding exposure variables were scaled to raw dollar amounts in fiscal year 2019 $s, with all study years represented (including pre-trend years in which NC Pre-K funding exposure was equal to 0 for students in all counties). School-district average achievement in reading/math was measured at third grade and achievement growth in reading/math was measured from third to eighth grade. All values of school-district average achievement and achievement growth were "current year minus 1."

Table S4

Analyses to Examine the Association between Program Funding Exposure and School-District Average Achievement & Achievement Growth (N = 2,070)

	Reading				Math			
	Average Achievement		Achievement Growth		Average Achievement		Achievement Growth	
Parameter	*B*	(*SD*)	*B*	(*SD*)	*B*	(*SD*)	*B*	(*SD*)
NC Pre-K funding exposure	0.00	(0.02)	0.03	(0.02)	0.00	(0.03)	–0.01	(0.05)

Note. The generalized equation for these analyses was:

$$O_{sPy+4} = \beta_0 + \beta_1 NC\ PreK\ funding_{cPy} + \alpha_c + \gamma_{Py} + \alpha * \gamma_{cPy} + \epsilon_{scPy}$$

O is the school-district average achievement or achievement growth score for school district *s* in county *c* aligned to program year *Py* + 4, β_1 is the main effect of NC Pre-K funding in county *c* and program year *Py*, α is the fixed effect for county, and γ is the fixed effect for program year. School-district achievement and school-district average achievement growth information was aligned to county-level program funding information in program year *Py* + 4 (e.g., students' exposure to NC Pre-K program funding during program year 2000 was aligned to the average achievement and achievement growth values for the cohort of students enrolled in third grade four years later during school year 2004, which is the school year in which these students were expected to be in third grade), and all values of school-district average achievement and achievement growth were "current year minus 1", which was consistent with the approach used in our eighth-grade student achievement analyses. The effect of NC Pre-K funding exposure is equal to a change from $0 to $2,030. All models were estimated with robust standard errors clustered at the county level. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Table S5

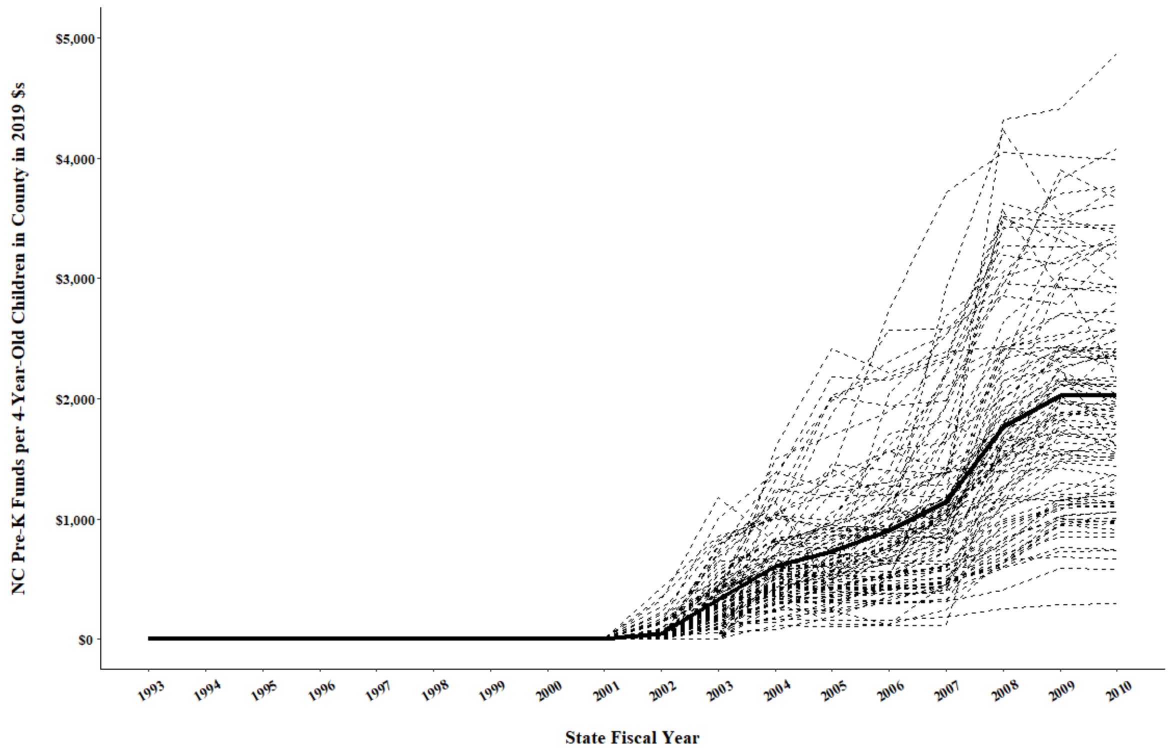
Eighth-Grade Student Achievement Analysis Results: Excluding Average Achievement and Achievement Growth

	Reading		Math	
	N = 1,160,725		N = 1,123,347	
Parameter	β	(*SE*)	β	(*SE*)
NC Pre-K funding exposure	0.08^{***}	(0.02)	0.11^{*}	(0.04)
Covariates	Inc.		Inc.	
County fixed effects	Inc.		Inc.	
Program year fixed effects	Inc.		Inc.	
Linear time trends	Inc.		Inc.	
R-squared	0.27		0.27	

Note. Parameter estimates for the student, school-district, and county covariates; county fixed effects; program year fixed effects; and linear time trends are not displayed in Table S5, but can be made available from the corresponding author upon request. The effect of NC Pre-K funding exposure is equal to a change from $0 to $2,030. All models were estimated with robust standard errors clustered at the county level. $^{\dagger}p < .10$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$

Figure S1

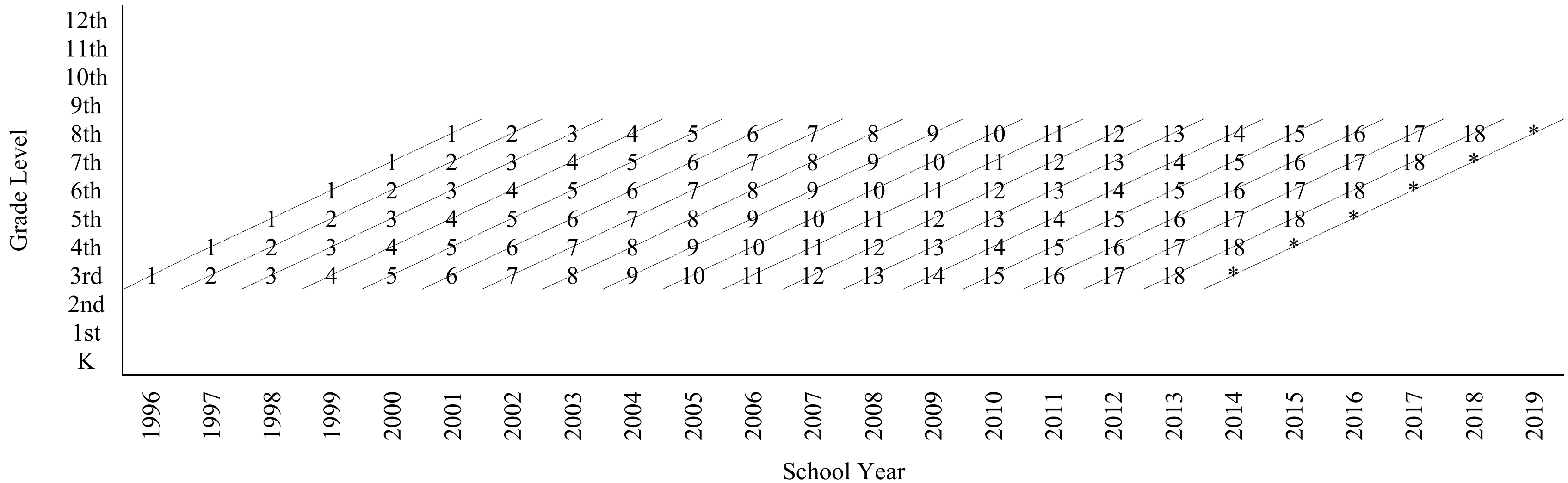
NC Pre-K Funds per 4-Year-Old Children in County: 1993 to 2010



Note. All counties with statewide average. Dotted lines represent individual counties. Solid line represents statewide average. NC Pre-K was established in state fiscal year 2002. In the student outcome analyses, all counties were assigned a pre-trend value of "0" prior to the establishment of NC Pre-K in state fiscal year 2002.

Figure S3

North Carolina Third to Eighth Grade Student Cohorts between 1996 and 2018 (N = 18)



Note. Each diagonal line corresponds to a cohort of students. In Phase I of our analyses, a separate growth curve model was estimated for students in each cohort, which was used to calculate the intercept (i.e., third grade average achievement) and slope (i.e., achievement growth between third and eighth grade) in reading and mathematics for each school district within each cohort. These estimates were then used in Phase II of our analyses to examine moderation of the long-term effect of NC Pre-K. Students in the cohort indexed by the asterisk were included in the Phase II analyses, but not the Phase I analyses because of the "current year minus 1" approach.