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The role of executive function in shaping the longitudinal stability of math achievement during early elementary grades

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ABSTRACT

There is substantial rank-order stability in children's mathematical skills throughout development. Research has shown that children who enter school with relatively low math skills are unlikely to catch up to peers who begin kindergarten with more developed math skills. Emerging evidence suggests that children's executive function skills might play an important role in shaping the rate and stability of mathematical skill development during early development. Therefore in the present study, we used data from the Early Childhood Longitudinal Study-Kindergarten Cohort 2010-11—a prospective sample of over 18,000 children in the United States—to examine executive function as an antecedent to characteristics of growth in math skills and to test whether executive function moderates the longitudinal stability of math achievement from kindergarten through second grade. Latent growth curve models reveal that executive function is related to not only the level of math skills at school entry but also to the rate of growth in early elementary years. Moreover, we found that executive function moderated the stability of math achievement from kindergarten to second grade, suggesting that early executive function skills can serve as a compensatory mechanism for children who enter school with lower levels of mathematical skills. These findings might have important implications for narrowing gaps in math achievement during early elementary school.

Introduction

The transition to kindergarten is characterized by a period of rapid change for young children. For many, kindergarten marks the first time children are expected to attend to direct instruction and gain a mastery of academic content knowledge. As a result, children's academic skills undergo rapid development during the early school transition period (Kim et al., 2021; Morrison et al., 2019). Notably, this early period of formal schooling is critical for children's mathematical development. For example, U.S. national test scores suggest that children make the most rapid gains in math achievement during the first few years of formal schooling compared to later developmental periods, including during late childhood and adolescence (LoGerfo et al., 2006). However, despite this accelerated period of math growth, there is also considerable heterogeneity in children's math skills at school entry, likely due to differences in educational experiences, skills, and knowledge before children enter kindergarten (e.g., Magnuson et al. 2004; Raver et al. 2007). Moreover, differences in children's math skills at school entry appear to remain constant across development—that is, there is considerable rank-order stability in children's math skills from kindergarten through high school (Davis-Kean et al., 2021; Duncan et al., 2007; Jordan et al., 2009). The rank-order stability in children's math development has the biggest implications for the lowest performing students in that it suggests that children who enter school with low math skills are unlikely to catch up to peers who begin kindergarten with more developed math skills.

Despite this, recent evidence suggests that children's cognitive skills might play an important role in shaping the rate of mathematical skill development. For example, two recent studies have found that children's executive function (EF) skills moderated gains in children's mathematical skills across kindergarten and first grade (Blair et al., 2016), as well as from pre-kindergarten to fifth grade, suggesting that EF can play a compensatory role by attenuating the stability in math achievement across elementary school (Ribner et al., 2017). However, these studies relied on two timepoints to assess the stability of math, limiting the inferences drawn about the development and stability of children's math skills, as well as EF's role in shaping the rank-order stability of math achievement across elementary school. Therefore, in the present study, we use a latent growth curve modeling approach to 1) test whether EF at kindergarten entry predicts initial levels and the rate of growth in

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mathematical skills from kindergarten through second grade, and 2) examine whether EF at kindergarten entry moderates the longitudinal stability of math achievement from kindergarten through second grade.

The early development of math skills

Decades of research has highlighted the importance of the early childhood period for the development of children's math skills (e.g., Duncan et al. 2007; Watts et al. 2014). Like learning how to read, children's early math skills appear to develop linearly, with advanced mastery relying on an understanding of basic math concepts. This is perhaps due to the hierarchical structure of math wherein children must master basic skills to effectively build an understanding of more advanced concepts. For example, a child's understanding of operations and fractions are reliant upon a firm understanding of cardinal values of integers (Clements & Sarama, 2014). However, the linearity of math development can also create gaps in children's math trajectories over time, underscoring the importance of the early development and mastery of basic math skills (e.g., Claessens et al. 2009; Duncan et al. 2007; Watts et al. 2014).

Studies using a wide range of populations and measurement strategies consistently find that children's early understanding of numbers, counting, and arithmetic is strongly related to students' mathematical achievement across schooling (Claessens & Engel, 2013; Duncan et al., 2007; Geary, 2013; Jordan et al., 2009; Stevenson & Newman, 1986; Watts et al., 2014, 2017). This early mastery of basic mathematical concepts is also related to children's math performance across development, even when accounting for domain-general child cognitive skills (e.g., intelligence, language skills, self-regulation; Blair et al. 2016, Xenidou-Dervou et al. 2018), teacher and classroom characteristics (e.g., classroom quality; teacher-child relationships; Blankson & Blair 2016; Blair et al. 2016), and household characteristics (e.g., family socioeconomic status, household structure; Morgan et al. 2019, Watts et al. 2014).

The longitudinal stability of math skills

Students who enter school with relatively high levels of math skills tend to maintain an advantage over peers who begin school with lower levels of math skills (Duncan et al., 2007; Watts et al., 2014). Duncan et al. (2007) offer one of the strongest demonstrations of this: Meta-analytic results across six large-scale longitudinal datasets from three Western countries demonstrated that math was the strongest predictor of both math and reading skills at a range of later time points, more so than were background characteristics, reading, attention, and socioemotional skills, and subsequent replications and extensions have demonstrated the robustness of these findings (Ahmed et al., 2019; Grimm et al., 2010; Pagani et al., 2010; Romano et al., 2010). Early math skills even prior to school entry have been shown to predict important educational outcomes, including enrolling in advanced math courses during high school and the likelihood of enrolling in college (Davis-Kean et al., 2021).

Executive function and math development

EF—a multidimensional construct made up of skills recruited in the pursuit of goals and is implicated in the regulation of thoughts, behaviors, and emotions—is robustly related to math throughout the lifespan (e.g., Ahmed et al. 2022; Bull & Lee 2014; Jacob & Parkinson 2015). The skills that comprise EF include inhibitory control—the ability to resist a prepotent response in favor of one that is more contextually appropriate or correct—working memory—the ability to keep in mind and manipulate multiple pieces of information—and cognitive flexibility—the ability to effectively shift between multiple relevant stimuli (Diamond, 2013; Miyake et al., 2000). EF is thought to support both individual aspects of doing mathematics including computation (e.g., Ribner et al. 2018) and the acquisition of new mathematical skills (Cragg & Gilmore, 2014).

Decades of research have suggested aspects of children's domain-general cognitive skills—including EF—might underlie the ability to effectively and efficiently process information, thus enabling children with higher EF to develop skills at a more rapid pace than peers with lower levels of EF (Case, 1992; Case et al., 2001; Miller, 1956; Nyikos & Oxford, 1993). Several studies support this theoretical claim that EF is a robust predictor of the growth of mathematical skills over time: Net of earlier math skills and a wide range of covariates including general intelligence, processing speed, and language skills, EF at school entry predicts mathematical skills at various points across elementary school (e.g., Blair et al. 2016, McClelland et al. 2014, Ribner et al. 2017, Schmitt et al. 2017, Waters et al. 2021), and beyond (e.g., LeFevre et al. 2013).

Although a number of studies have shown that early EF predicts later math, few have explored the extent to which EF is associated with the trajectory of growth in mathematical skills over time. Given the substantial rank-order stability in math, it is possible that much of the association of any other domain-general child-level skills (including EF) with math is limited to children's skill level at school entry (i.e., intercept effects), and have little to no lasting relation to the relative rate of learning in school settings (i.e., slope effects). Better understanding the role of EF in the development of mathematical skills over time—not just in children's starting level of skills—might have implications for teaching, as it might be important to foster the development of EF to maximize students' learning potential.

Relatively few studies have investigated the role of EF in the development of math skills over time using methodologically robust analytic approaches to understanding growth, and those studies have reported inconsistent findings as to whether EF is associated with growth in skills over and above its relation to school entry math. One study showed that EF at age 4 was associated with the level of math at age 5, but not with growth from Pre-K to second grade when cognitive covariates and other dimensions of self-regulation were taken into account (Blair et al., 2015). In contrast, others have demonstrated a robust association between EF and the slope of math development from kindergarten through second grade (Aunola et al., 2004), kindergarten through third grade (Morgan et al., 2019), and from kindergarten through fifth grade (Geary, 2011). Given these inconsistent findings, further investigation is needed to better understand relations between EF and the development of math skills over time.

Executive function and the stability of math development

Beyond associations between EF and the level and/or rate of growth in mathematical skills, there is emerging evidence that EF may serve as a compensatory skill for children who enter elementary school with low levels of mathematical skills. That is, children who enter school with relatively lower levels of math but higher levels of EF than their peers might develop mathematical skills at a faster rate, giving them the opportunity to catch up to their peers (Blair et al., 2016; Ribner et al., 2017), potentially due to differences in learning from instruction (cf. Ribner, 2020). Two studies to date have explored EF as a moderator of gains in mathematical skills across elementary grades, specifically between math prior to kindergarten entry and scores on tests of mathematical skills in kindergarten (Blair et al., 2016) and fifth grade (Ribner et al., 2017). However, both of these prior studies used autoregressive approaches and used the same dataset. Nevertheless, investigations of the relation between EF and the development of mathematical skills present a compelling case for the idea that EF may be a critical skill underlying the rate of mathematical skill development over time, and described associations may reflect that high levels of EF enable children to learn more effectively and efficiently. In the present study, we seek to test whether EF moderates the development of mathematical skills such that it can compensate for lower levels of school entry math. We do this by using more methodologically rigorous methods and a larger and more geographically, linguistically, socioeconomically, and racial/ethnically diverse population than has been used in prior studies.

Current study

The cross-sectional and prospective relations between EF and math are well documented and robust; however, there is little consistency in findings regarding the role of EF in the growth of math skills over time over and above the starting point. It is possible that the effect of EF is limited to children's skill level at school entry (i.e., intercept effects) and there is little to no lasting effect on the relative rate of children's learning in school settings (i.e., slope effects). Therefore, further research is needed to better understand the role of EF as an antecedent to growth in math skills in early grades. Beyond potential associations of EF with children's starting point and/or rate of growth in mathematics, there is a need for additional research testing the hypothesis that EF can moderate the rate of mathematical skill development such that children with low levels of math skills at school entry, but high EF may be able to leverage their EF skills to catch up to their peers who enter school with higher levels of math skills. We leverage data from the Early Childhood Longitudinal Cohort-Kindergarten Class of 2010-11 (ECLS-K:10), a large dataset representative of children across the United States and from a wide range of sociocultural backgrounds to investigate three primary research questions:

(1) What is the pattern of mathematical skill development for the average child in early elementary grades? As with prior investigations (e.g., Cameron et al. 2015), we anticipate a non-linear growth function whereby growth in mathematical skills begins fast and decelerates over time.
(2) Does EF at school entry predict the rate of math growth from the beginning of kindergarten through the end of second grade? We expect that children who enter kindergarten with better performance on EF tasks will have a faster rate of growth in math skills from kindergarten to second grade.
(3) Does EF moderate the development of math skills whereby children who enter school with low levels of math but high levels of EF develop math at a faster rate than those who enter school with higher levels math skills and/or lower levels of EF? We anticipate that EF will moderate the relation between the starting point and rate of growth, such that children with high EF but a low starting point in math will develop math skills more rapidly than will those who start with low EF and math, thus giving them the opportunity to “catch up” (or narrow the gap) between them and those with higher initial skills.

Methods

Participants

Participants were recruited for the ECLS-K:10, a sample of 18,174 kindergarteners drawn from 968 schools. A full description of the sampling procedure can be found elsewhere (Tourangeau et al., 2015). The analytic sample is restricted to 12,082 (52% female) students. Participants were excluded if they did not take part in the fall kindergarten wave of data collection ($n = 2{,}390$); if they were in a non-target grade, either for reasons of grade repetition or grade skipping ($n = 1{,}903$); or had a recorded individualized education plan (IEP) at any data collection time point ($n_{K\text{-}2} = 2{,}413$; $n_K = 1{,}396$; $n_{1st} = 1{,}278$; $n_{2nd} = 1{,}518$). Students included in analyses were, on average, 66.18 months of age at kindergarten entry ($SD = 4.58$) and were enrolled in 968 schools. Unsurprisingly, the analytic sample differed from the full sample given previously described associations between target grade enrollment and family/child sociodemographic characteristics, as well as between IEP receipt and family/child sociodemographic factors.

Participants retained for the analytic sample were more likely to be from higher-SES homes ($M_{excluded}$ = -0.18, SD = .81; $M_{analytic}$ = 0.00, SD = 0.81; $t(16003) = -13.17$, $p < .001$), be older at kindergarten entry ($M_{excluded}$ = 66.52 months, SD = 4.10; $M_{analytic}$ = 64.67 months, SD = 5.83; $t(15867) = -21.66$, $p < .001$), be female (Excluded = 42.5% female; Included = 51.9% female; $\chi^2(1) = 143.10$, $p < .001$), and be white (Excluded = 31.6% white; Included = 36.3% white; $\chi^2(1) = 31.76$, $p < .001$). Similar patterns were seen at the school level: Participants retained for the analytic sample were more likely to attend schools which had a lower proportion of non-white students ($M_{excluded}$ = 53.18%, SD = 34.12; $M_{analytic}$ = 46.69, SD = 31.15; $t(17805) = 12.01$, $p < .001$), had a lower proportion of students eligible for free ($M_{excluded}$ = 46.59%, SD = 30.12; $M_{analytic}$ = 41.47, SD = 32.06; $t(17818) = 10.32$, $p < .001$) and reduced price ($M_{excluded}$ = 8.19, SD = 8.34; $M_{analytic}$ = 7.93, SD = 9.02; $t(17818) = 5.70$, $p < .001$) lunch, and were less likely to be in a school in an urban setting (Excluded = 25.5% urban; Included = 29.1% urban; $\chi^2(1) = 22.95$, $p < .001$). Research ethics committee approval was not sought given the nature of this investigation as a secondary data analysis; ethics approval for data collection was performed by the National Center for Education Statistics.

Procedures

Data were collected through direct child assessment and parent interviews in the fall and spring of each kindergarten, first, and second grade. Participants completed a reading assessment, math assessment, and EF assessment in a standardized order in a quiet school setting. In the fall of the first and second grade years, only a subset of students who were representative of the full sample completed assessments (first grade $n = 3{,}409$; second grade $n = 3{,}065$). Selection procedures are described elsewhere (Tourangeau et al., 2018). Data for parent interviews are drawn from the kindergarten year.

Measures

Math skills

The ECLS-K math assessment contained items designed to measure children's conceptual understanding, procedural knowledge, and problem-solving skills. Items assessed children's skills in six general domains: Number sense; measurement; geometry and spatial sense; data analysis, statistics, and probability; and patterns, algebra, and functions. The assessment was administered on an easel so participants could see stimuli, and text presented on the page was read aloud to reduce the likelihood that math assessment was dependent on reading skills. Participants completed a set of routing items at each assessment, which routed them to a second block of items of low, medium, or high difficulty. Reliability and validity have been reported elsewhere (Tourangeau et al., 2015). IRT scale scores are used to assess growth over time and scores range from 0-113 for each wave of data collection. Reliability of IRT-based scores was very high for each wave of math assessment and ranged from .92-.94.

Executive function

EF was assessed using two measures: The Dimensional Change Card Sort (DCCS; Zelazo, 2006) and Numbers Reversed (Mather & Schrank, 2001)that ostensibly measured cognitive flexibility and working memory, respectively. While there was no measure of inhibitory control—considered to be a third component of EF—in the early years of the ECLS-K, it is important to note the inherent inability to fully distinguish between purported components of EF. For example, the DCCS and Numbers Reversed both place demands on response inhibition in that the DCCS requires participants to override a trained response in the switch phase and Numbers Reversed requires participants to repeat the numbers in a different order in which they were uttered rather than provide the dominant response to repeat them exactly.

In accordance with findings that EF is best measured as a unitary construct in early childhood years (Brydges et al., 2012; Wiebe et al., 2011; Willoughby et al., 2012), a score representing each child's overall EF was created using the mean of *z*-scores from both assessments at each time point. Data from the time point closest to school entry (i.e., fall kindergarten) was used; scores were moderately correlated between tasks, $r = .30$, $p < .001$.

DCCS

In the DCCS, participants were instructed to sort cards into different piles based on a changing set of rules. Participants were instructed to sort cards by color (i.e., red or blue), then by shape (i.e., rabbit or boat). Finally, children moved to a third sorting rule: If the card had a black border, the child had to sort by color; if the card did not have a black border, the child had to sort by shape. A hard-copy, tabletop version with 22 cards described in Zelazo (2006) was used. If participants were correct for 4 of 6 items in the shape task would they then move on to sort by border color. Total correct out of 18 (6 color, 6 shape, 6 border) was used. Previous research shows that the DCCS has good test–retest reliability (Intraclass correlation [ICC] = .92) as well as strong construct and temporal stability over time (Zelazo et al., 2013).

Numbers reversed

The Numbers Reversed task was obtained from the *Woodcock-Johnson III Test of Achievement* (Mather et al., 2001), and was administered according to publisher instructions. Participants were instructed to verbally repeat an increasingly long string of numbers presented orally in reverse order, such that if the child was told the numbers "1…5" a correct response would be "5…1". Administration stopped when the child got three consecutive sequences incorrect or when children completed all sequences. An age-standardized *W* score was used for the Numbers Reversed task. The Numbers Reversed task shows good split-half reliability (a = .84 to .93), is associated with academic achievement (Morgan et al., 2019), and is related to other established measures of working memory.

Covariates

Covariates were chosen on the basis of whether they were theoretically and empirically related to children's performance on tests of mathematical and cognitive skills or development thereof over the course of a school year, or with teacher's instruction. As there is an extensive literature on the multidimensional influences on children's cognitive skills at the individual, family, classroom, and school levels (e.g., Burchinal et al., 2002, Duncan et al. 2007, Pace et al. 2019, Purpura et al. 2011), several covariates were chosen to attempt to estimate the association of key predictor variables with the development of mathematical skills.

Parent interviews

Covariates include indicators for child race/ethnicity, sex, and the primary type of non-parental care the child received the year prior to kindergarten. Various household characteristics are included as indicator variables, including type of parent(s) in the household as reported in the fall of kindergarten (i.e., two biological/adoptive parents, one biological/adoptive parent and one other parent/partner, one biological/adoptive parent only, and other guardians) and whether the home language was English. Continuous variables included control for household size and family socioeconomic status (SES). The measure of SES was created by the ECLS-K team from parent interview data using five items: Parent 1's highest level of education, parent 2's highest level of education, parent 1's occupational prestige, parent 2's occupational prestige, and household income. The value of each was *z*-scored, and an average of the *z*-scores was computed.

Direct assessment variables

All analyses control for the IRT scale score from the standardized measure of reading skills as a control for general cognitive ability and understanding of assessment, particularly given the previously described association between language abilities and both performance on assessments of mathematical skills (e.g., Purpura et al. 2011) and on assessments of EF (Kuhn et al., 2016). Models control for scores from the fall of kindergarten.

School administrator-reported variables

Finally, a small number of covariates obtained from a school administrator-completed questionnaire was included to control for school-level characteristics. Indicator variables were included for whether a school was large or small (0 = < 500 students; 1 = ≥ 500 students), whether a school was in a non-urban (0) or urban setting (1), and whether a school was private (0) or public (1). Continuous variables were included to estimate the proportion of the school who qualified for free lunch, reduced-price lunch, and the proportion of the school that was an ethnic/racial minority (i.e., non-white). All estimates were from the kindergarten year.

Data analysis plan

To investigate the first question addressing common trajectories of mathematical skill development in early elementary grades, an unconditional latent growth curve model (LGCM) was first estimated to assess the average growth pattern across the sample. To determine the number of LGC factors that best fit the data, model fit of a LGCM with intercept and linear slope parameters was compared to model fit of a LGCM with an added quadratic slope parameter and with an added cubic slope parameter. Cut-off criteria presented by Hu and Bentler (1999) were used: A well-fitting model was expected to have a Comparative Fit Index (CFI) of .95, and Root Mean Squared Error of Approximation (RMSEA) of .08. Linear slope time points were set in period of six months such that each fall testing time point was set to 1 (6 months) from the respective spring time point, and the fall of each year was set at an interval of 2 from the prior year.

To address the second question regarding the relation between EF at school entry and both the level and rate of growth of mathematical skills in early elementary grades, models were built upon those described above. Using the best-fitting LGCM for the average developmental trajectory, growth parameters were regressed on start-of-school EF and covariates. To address the final question as to whether EF moderates the development of mathematical skills, a LGCM was fit with an added interaction term between the intercept of math growth and EF at school entry. Simple slopes were tested at 1SD above and below the mean of EF (Cohen et al., 2003).

All models were estimated using Mplus 8 (Muthén & Muthén, 2017) with standard errors clustered within the school in which the child was enrolled for the kindergarten year. Despite availability of sample weights to make estimates nationally representative, weights were not used due to exclusionary criteria enacted that removed over 6000 cases from the full sample to make up the analytic sample as has been done previously by others (e.g., Morgan et al. 2019). As such, we do not consider estimates to be nationally representative, but only representative of the participants who completed data collection. Missing data were accounted for using Full Information Maximum Likelihood (FIML) estimation. FIML leverages the covariance matrix for all available data on the independent variables to estimate parameters and standard errors (Enders, 2001). We included child- and family-level variables that demonstrated significant differences between participants with missing and non-missing data as covariates in our final models to reduce the potential bias caused by missing data patterns and to adhere to MAR assumptions (Enders, 2010).

Results

Descriptive statistics for all variables included in analyses are presented in Tables 1 and 2. Bivariate correlations are presented in Table 3.

Research question 1: how does math develop in early elementary years?

Unconditional latent growth curve model

Six models were compared to estimate a normative pattern of growth for the six assessment timepoints in the fall and spring of each grade. Fit characteristics and details for each model are presented in Table 4. In Models 1-5, means and variances of freely estimated parameters were significant. In Model 6, variances of linear and quadratic slope were not significant (*p*s > .05). The best-fitting LGCM was the model with freely estimated intercept, linear slope, and quadratic slope parameters (Model 4) and was retained for further analysis.

The retained LGCM fit well, $\chi^2(12) = 1151.165$, $p < .0001$, RMSEA = 0.089 90% CI[.084, .093], CFI = 0.965, SRMR = .089. The intercept was correlated with both linear ($r = .39$, $p < .001$) and quadratic slope ($r = -.52$, $p < .001$) such that students who started school with higher levels of math skills also developed further skills at a faster rate and had a slower degradation of linear slope than did peers who started school with lower levels of skills. Linear and quadratic slope were strongly correlated ($r = -0.89$, $p < .001$) such that students who had faster rates of growth in math also saw a slower decline to their rate of growth over time.

Table 1
Descriptive statistics for continuous variables.

	N	Mean	SD	Range
Math Fall Kindergarten	12082	32.79	11.05	7.19-111.58
Math Spring Kindergarten	11591	46.88	11.26	11.75-88.76
Math Fall 1st Grade	3406	54.90	13.77	17.98-106.75
Math Spring 1st Grade	9909	69.55	13.55	23.32-109.01
Math Fall 2nd Grade	3065	73.23	12.72	20.33-106.30
Math Spring 2nd Grade	9026	83.68	11.16	12.20-19.75
Executive Function Kindergarten	12074	0.00	0.80	-2.87-2.97
Reading Fall Kindergarten	12060	47.91	11.42	25.45-109.92
Age at Kindergarten Entry	12077	66.52	4.10	48.33-84.03
Number Children in Household	10143	2.05	0.69	1-7
Number Adults in Household	10143	2.48	1.10	1-13
Family Socioeconomic Status	10957	0.00	0.81	-2.33-2.60
School Free-Lunch Eligible %	11752	41.56	32.03	0-100
School Reduced-Price Lunch Eligible %	11752	7.41	9.02	0-100
School Proportion Non-white	11742	46.80	34.12	0-100

Table 2
Frequencies of categorical variables.

Characteristic	Frequency	Percent
Female	6262	51.8
Mother Married at Time of Birth	7131	59
Primary Household Language English	9070	75.1
Household Structure		
Two Biological/Adoptive Parents	7179	70.5
One Biological/Adoptive Parent & One Other Parent/Partner	690	5.7
One Biological/Adoptive Parent Only	2122	17.6
Other Guardians	186	1.5
Child Race		
White, Non-Hispanic	5955	49.3
Non-White	6094	50.7
PreKindergarten Setting		
No Non-Parental Care	2107	17.4
Relative Care in Child's Home	1582	13.1
Non-Relative Care in Child's Home	670	5.6
Center-Based Program	5944	49.2
Two or More Types of Care with Equal Hours	282	2.3
School in Urban Setting	7297	61.9
School Large (≥ 500 Students)	5968	50.8
School Private	1682	14.3

Research question 2: does EF predict growth in math?

Conditional LGCM

Beyond covariates, EF was associated with the intercept, $\beta = 0.26$, $p < .001$. That is, students with higher EF at the beginning of kindergarten, on average, started school with higher levels of math skills. EF was also associated with the linear slope such that students with higher EF developed math skills at a faster rate than did those with lower EF, $\beta = 0.19$, $p < .001$. As well, students with higher EF had a slower degradation of linear slope as evidenced by the negative association with the quadratic slope term, $\beta = -0.18$, $p < .001$. These findings confirm the tested hypothesis that higher EF at the start of school would be associated with faster rate of growth in math skills.

Research question 3: does EF moderate the rate of mathematical skill development?

To test whether EF can play a compensatory role in the development of math skills for students who enter school with lower levels of math, another model was tested to examine whether the interaction between start-of-school EF and math intercept was related to linear math slope. The association of the interaction of EF with the intercept, though statistically significant, was small, $\beta = -0.04$, $p = .017$. Examination of simple slopes revealed the magnitude of the association of intercept with slope did not differ to a great extent for children with EF 1SD below the mean ($\beta = 0.59$, $p < .001$) compared with those with mean levels of EF ($\beta = 0.55$, $p < .001$) or those with EF 1SD above the mean ($\beta = 0.51$, $p < .001$); however, as the effect is on the rate of growth, it might still be meaningful over time.

Discussion

This study used data from the ECLS-K:10 to investigate the relations between children's EF at school entry and patterns of development of math skills from the beginning of kindergarten through the end of second grade. We found that students with higher EF at kindergarten entry, on average, started school with higher levels of math skills and developed math skills at a faster rate than did those with lower EF. Additionally, we found that EF significantly moderated the stability of math achievement from kindergarten to second grade, suggesting that early EF skills can serve as a compensatory mechanism for children who enter school with lower levels of math skills.

Executive function and growth in math achievement

This is the first study to analyze relations between EF and growth parameters of math in the ECLS-K:10. Consistent with the large literature documenting relations of EF and math in early childhood, EF predicted all growth parameters across all analyses. This study used methodologically robust analyses to conclude that EF predicts not only the starting point of children's skills, but also the rate at which those skills develop. EF emerged as the strongest predictor of linear and quadratic slopes and was second only to reading skills in predicting the intercept. That reading was more strongly related to the intercept than was EF is unsurprising given the language demands of the math assessment and the overlap in task demands (cf. Purpura et al., 2011).

Results of prior investigations of the relation between EF and growth in math have been mixed in that some demonstrate a relation

Table 3
Correlations among child- and family-level study variables.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	Math Fall K	—																						
2	Math Spring K	.80***	—																					
3	Math Fall 1st	.76***	.82***	—																				
4	Math Spring 1st	.73***	.78***	.81***	—																			
5	Math Fall 2nd	.70***	.76***	.77***	.85***	—																		
6	Math Spring 2nd	.67***	.73***	.73***	.82***	.86***	—																	
7	EF Fall K	.58***	.55***	.52***	.53***	.51***	.51***	—																
8	Reading Fall K	.75***	.64***	.61***	.56***	.53***	.50***	.49***	—															
9	Child Female	-.04***	-.04***	-.04*	-.10***	-.09***	-.12***	.03**	.03***	—														
10	Child Non-White	-.05***	-.09***	-.04*	-.13***	-.03	-.13***	-.11***	.02*	.02*	—													
11	Home Lang. English	.19***	.18***	.22***	.21***	.26***	.19***	.20***	.15***	.00	-.08***	—												
12	Center-based PreK	.15***	.10***	.10***	.09***	.09***	.08***	.10***	.15***	-.01	.02	.06***	—											
13	Relative Care PreK	-.09***	-.07***	-.04*	-.06***	-.05*	-.07***	-.06***	-.08***	.02*	.03**	-.01	-.47***	—										
14	Non-Relative Care PreK	.04***	.05***	.03	.06***	.05*	.05***	.04***	.00	-.01	-.06***	.07***	-.29***	-.11***	—									
15	2+ PreK	.03**	.02*	.01	.03**	.01	.04**	.04***	.02	.00	-.01	.03***	-.19***	-.07***	-.04***	—								
16	Two Parent	-.06**	-.06***	-.04*	-.04***	-.04*	-.03**	-.03**	-.07***	.00	-.04***	.06***	-.03**	.02	.02*	.00	—							
17	One Parent	-.17***	-.17***	-.16***	-.18***	-.20***	-.22***	-.13***	-.14***	.01	.20***	.05***	-.05***	.13***	-.02*	.00	-.14***	—						
18	Other Guardian	-.05***	-.05***	-.04*	-.07***	-.04*	-.06***	-.04***	-.05***	.00	.05***	.03**	-.01	.00	-.02	.01	-.04***	-.07***	—					
19	Mom Unmarried Birth	-.25***	-.25***	-.22***	-.26***	-.28***	-.27***	-.18***	-.22***	.01	.18***	-.01	-.08***	.09***	-.03**	-.02*	.19***	.38***	.14***	—				
20	Age K Entry	.25***	.23***	.20***	.19***	.12***	.14***	.16***	.16***	-.07***	-.07***	.10***	-.01	-.03*	.03**	.00	.02	.00	.01	-.01	—			
21	Family SES	.43***	.40***	.40***	.41***	.43***	.41***	.32***	.40***	-.01	-.05***	.27***	.18***	-.09***	.05***	.03**	-.12***	-.29***	-.07***	-.42***	.01	—		
22	# Household <18	-.10***	-.08***	-.08***	-.08***	-.09***	-.06***	-.07***	-.12***	.00	.00	-.03**	-.06***	-.03**	-.03**	-.04***	.02	-.06***	-.01	-.04***	.04***	-.09***	—	
23	# Household 18+	-.03**	-.03**	-.05**	-.03**	-.05**	-.01	-.04***	-.02	.02	-.03**	-.16***	-.05***	.07***	-.04***	-.01	.06***	-.32***	.00	-.05***	-.04***	-.01	.05***	—

Note:
*** $p<.001$,
** $p<.01$,
* $p<.05$; K—Kindergarten; EF—Executive function; PreK—PreKindergarten; Lang—Language; SES—Socioeconomic Status

Table 4
Model fit indices for unconditional latent growth curve models.

	Model	χ^2	df	RMSEA (90%CI)	CFI	TLI
1	Free Intercept, Fixed Slope	6862.854	18	0.177 (.174, .181)	0.788	0.824
2	Free Intercept, Free Slope	6477.729	16	0.183 (.179, .187)	0.800	0.813
3	Free Intercept, Free Slope, Fixed Quadratic	2095.049	15	0.107 (.103, .111)	0.936	0.936
4	**Free Intercept, Free Slope, Free Quadratic**	**1151.165**	**12**	**0.089 (.084, .093)**	**0.965**	**0.956**
5	Free Intercept, Free Slope, Free Quadratic, Fixed Cubic	1198.762	11	0.095 (.090, .099)	0.963	0.950
6	Free Intercept, Free Slope, Free Quadratic, Free Cubic	905.550	7	0.103 (.097, .109)	0.972	0.940

between EF and children's starting point in math, whereas others find little to no effect of EF on the rate of math skill development over and above the starting point (e.g., Aunola et al. 2004, Geary 2011; but, see Blair et al. 2015). Although an increasingly large literature describes a robust association between EF and math, it is possible that much of this association is due to a correlation between EF and math skills early on and that EF has little to do with math development over time. Thus, it is important to consider several distinctions that might be at the root of these inconsistent findings. It is noteworthy that while two of these prior investigations have found relations between EF and growth in math, those studies used only a subset of what is commonly construed as EF: One study (Aunola et al., 2004) used a measure of visual attention, which only predicted the slope term but not the intercept; the other (Geary, 2011) used several aspects of working memory which similarly predicted only slope. Blair et al. (2015)—in contrast to this study—found performance on a comprehensive battery of EF at age 4 was positively associated with the intercept in math, but negatively with slope; however, the association was non-significant when accounting for other child-level characteristics (i.e., vocabulary and processing speed), and controlled for several other aspects of self-regulation for which data are not available here (i.e., effortful control, cortisol).

Executive function moderates growth in math achievement

Overall, children who entered school with higher levels of math skills continue to develop skills at a faster rate than did their peers who entered school with lower levels of skills and saw less of a decline to the rate of skill development. These findings align with theories of math learning trajectories (e.g., Clements & Sarama 2014) and support a large body of literature demonstrating the rank-order stability of stability in mathematics across development (e.g., Davis-Kean et al. 2021, Duncan et al. 2007, Jordan et al. 2009). Moreover we examined the interaction between children's EF and math achievement. A meaningful significant interaction between children's EF and math achievement would provide an important mechanism for the opportunity to aid in narrowing the gap between low and high achievers. We found that children's EF skills at kindergarten entry significantly moderated the rate of growth of math achievement from kindergarten through second grade. Although the effect size was relatively small (-.04), these findings align with a recent body of research suggesting that early EF can serve as a compensatory mechanism by which students who enter school with lower levels of math skills can catch up to their peers. However, we urge caution in interpreting this result as it may be an artifact of the large sample used in the current study. Thus, given this small effect, future research is needed to understand the robustness of these findings and the extent to which the compensatory role of early EF is sustained across development.

Importantly, the analyses presented in this investigation assume a particularly salient role of early EF (i.e., school entry) in the development of mathematical skills. This is partially predicated on the fact that kindergarten entry in the US is the point at which students have the greatest diversity of skills and past experiences, whereas in later grades students are more likely to have had more homogeneous previous experiences (e.g., exposure to curriculum, school structure). We acknowledge that there might be differential relations between EF and growth

Table 5
Results of regressions predicting growth in math skills.

	Intercept			Linear Slope						Quadratic Slope					
	Beta	SE	p-value	Beta	SE	p-value	Beta	SE	p-value	Beta	SE	p-value	Beta	SE	p-value
EF Fall Kindergarten	0.26	0.01	0.000	0.18	0.02	0.000	0.17	0.06	0.003	-0.18	0.02	0.000	0.12	0.06	0.057
Reading Fall Kindergarten	0.60	0.01	0.000	-0.15	0.02	0.000	-0.46	0.06	0.000	0.00	0.02	0.992	0.40	0.06	0.000
Child Female	-0.06	0.01	0.000	-0.06	0.02	0.000	-0.04	0.02	0.038	0.02	0.02	0.233	-0.02	0.02	0.384
Child Non-White	0.00	0.01	0.666	-0.07	0.02	0.003	-0.07	0.02	0.006	0.05	0.02	0.025	0.05	0.02	0.052
English Main Home Language	0.00	0.01	0.880	0.03	0.02	0.182	0.02	0.02	0.313	-0.06	0.02	0.011	-0.07	0.02	0.008
PreK Center Care	0.03	0.01	0.000	-0.11	0.02	0.000	-0.12	0.03	0.000	0.09	0.03	0.000	0.11	0.03	0.000
PreK Relative Care	0.02	0.01	0.021	-0.02	0.02	0.444	-0.02	0.02	0.258	0.01	0.02	0.780	0.02	0.02	0.468
PreK Non-relative Care	0.03	0.01	0.000	-0.02	0.02	0.299	-0.03	0.02	0.091	0.01	0.02	0.633	0.03	0.02	0.232
PreK Two or More Equal Care	0.02	0.01	0.026	-0.03	0.02	0.065	-0.04	0.02	0.028	0.03	0.02	0.094	0.04	0.02	0.046
Parent Plus Partner	-0.01	0.01	0.175	0.00	0.02	0.969	0.00	0.02	0.833	0.01	0.02	0.807	0.00	0.02	0.966
Single Parent	-0.03	0.01	0.000	0.00	0.02	0.932	0.02	0.02	0.505	-0.03	0.02	0.282	-0.04	0.03	0.083
Other Guardian	-0.01	0.01	0.142	-0.02	0.02	0.311	-0.02	0.02	0.461	0.02	0.02	0.451	0.01	0.02	0.650
Mom Unmarried Birth	-0.02	0.01	0.005	-0.07	0.02	0.002	-0.05	0.02	0.020	0.06	0.02	0.016	0.04	0.02	0.084
Age Enter Kindergarten	0.12	0.01	0.000	0.00	0.02	0.947	-0.06	0.02	0.003	-0.07	0.02	0.000	0.01	0.02	0.602
Family SES	0.08	0.01	0.000	0.09	0.03	0.001	0.04	0.03	0.105	-0.06	0.03	0.022	-0.01	0.03	0.762
# Children in Household	0.00	0.01	0.891	-0.02	0.02	0.272	-0.02	0.02	0.333	0.02	0.02	0.278	0.02	0.02	0.285
# Adults in Household	-0.01	0.01	0.113	-0.02	0.02	0.180	-0.02	0.02	0.308	0.03	0.02	0.118	0.02	0.02	0.234
School in Urban Setting	0.00	0.01	0.965	0.05	0.03	0.065	0.05	0.03	0.069	-0.05	0.03	0.092	-0.05	0.03	0.091
School Large (> 500 Students)	-0.01	0.01	0.330	0.01	0.03	0.843	0.01	0.03	0.716	-0.01	0.03	0.849	-0.01	0.03	0.722
School % Free Lunch	-0.05	0.01	0.000	0.07	0.05	0.136	0.09	0.05	0.054	-0.09	0.05	0.075	-0.12	0.05	0.027
School % Reduced Lunch	0.01	0.01	0.491	0.00	0.03	0.935	-0.01	0.04	0.843	0.02	0.03	0.536	0.02	0.04	0.511
School % Non-white	0.00	0.01	0.915	-0.17	0.04	0.000	-0.16	0.04	0.000	0.13	0.04	0.002	0.13	0.04	0.003
School Public	0.01	0.01	0.164	0.00	0.04	0.973	-0.01	0.04	0.809	-0.04	0.04	0.333	-0.03	0.04	0.518
EF Fall K * Intercept							-0.04	0.02	0.020				-0.05	0.02	0.012
Intercept Term							0.53	0.09	0.000				-0.63	0.08	0.000

Note: EF—Executive Function; PreK—PreKindergarten; K—Kindergarten in math at different points throughout children's educational experience, particularly given the fact that the two skills are correlated throughout school age (e.g., Best et al., 2011. However, specific to early elementary grades, prior studies (e.g., Ribner 2020) found that EF moderated the extent to which children learn from instruction in kindergarten but not in first or second grade, potentially highlighting the ways in which EF at school entry might be involved in the process of learning math. It is important for future research to investigate the specific longitudinal sequence in the relations between EF and the development of mathematical skills (as well as potential bidirectional associations) using some combination of cross-lagged panel models and random intercept cross-lagged panel models—ideally with multiple data collection time points within a given year—to better understand these temporal characteristics.

Educational implications

EF was related to not only the level of math at school entry but also the rate of growth in early mathematics skills. These findings might have several practical implications. First, they suggest that supporting children's EF skills prior to school entry could be one way to narrow gaps in math achievement across early elementary school. Indeed, recent research has demonstrated modest effects of preschool interventions on children's EF and academic outcomes (see Mattera et al., 2021 for review), however, whether these benefits can be sustained across elementary school is less understood (see Bailey et al., 2020 for commentary on fade-out effects). Additionally, given the limited evidence of transfer from EF training programs (see Goodrich et al. 2021), the effectiveness of EF interventions for placing children on different math trajectories remains unclear.

Alternatively, teaching strategies that are designed to support children's EF during learning, either through well designed learning materials or instruction, might be effective for children's math development. For example, Gathercole and Alloway (2008) demonstrated that deficits in working memory can be supported through visual aids and notetaking, or for spatial working memory, may rely on verbal strategies. Relatedly, some work suggests that shifting ability may moderate the effect of worked examples (Schwaighofer et al., 2016), suggesting that worked examples may also offer a form of support. However, much more research is necessary to understand whether teaching strategies that are designed to support children's EF can benefit children's early math development.

Finally, and consistent with the theory of mutualism (see Peng & Kievit 2020, for review), programs designed to promote early math development could have dual benefits for children's math and EF skills. For instance, recent research has shown that participating in an early math intervention benefitted children's EF skills (DeFlorio et al., 2019). It could be the case that early math programs offer children opportunities to practice EF strategies by, for example, holding math information in short-term memory for later use, or by shifting their attention to different task elements during math activities. Further research is needed to better understand the hypothesis of a mutual, reciprocal, or dynamic association between EF and math.

Limitations

Several limitations must be considered in the interpretation of these findings. First, it is important to note that though the data from the ECLS-K are correlational, and causality cannot be inferred. Though the analyses controlled for a host of child and family characteristics, it remains possible—and is indeed likely—that there are unmeasured between-student, between-family, and between-classroom differences that relate to the measurement and development of mathematical skills. Although observations are clustered within schools in which children are enrolled, these analyses do not consider characteristics of teachers, classrooms, or schools that might relate to rate of skill development. Second, there are a number of omitted variables that could not be considered in the present investigation. Aspects of the classroom context (e.g., classroom and instructional quality; Mashburn et al. 2008, Pianta et al. 2002, Ribner 2020), of the child (e.g., general intelligence, processing speed; Blair et al. 2015, Geary 2011), and of the home (e.g., home numeracy environment and parent math anxiety; Maloney et al. 2015, Melhuish et al. 2008, Skwarchuk et al. 2014), that are associated with the development of mathematical skills could not be included in analyses due to limitations in data availability.

Despite best efforts to control for as many external characteristics as possible given data availability, it is likely that children with higher levels of executive function are also better at completing standardized assessments. Third, it is important to note that constructs involved in the present investigation—notably EF and math—are complex, multidimensional, and difficult to measure. Further research is needed to test these questions to lend greater specificity to findings. Relatedly, it is important to note that EF was only considered at a single time point. Though this was central to the hypothesis that school entry EF relates to growth in math, it fails to consider ways in which EF might grow and change with—or in contrast with—early math skills. This approach also failed to consider the potential mutual or bidirectional associations whereby improving mathematical skills supports the emergence of more advanced EF (e.g., Clements & Sarama 2014, DeFlorio et al., 2019, Peng & Kievit 2020). Finally, additional research is needed to replicate these findings with other data and with different children in different contexts. Though a large-scale dataset is a powerful tool, these findings might be specific to a US context or to the temporal context of the early 2010s (i.e., cohort effects). Finally, the current investigation was limited in scope both in terms of the direction of associations (a unidirectional association wherein EF predicts growth in math was assumed, potentially obscuring a more dynamic or bidirectional association; cf. Cameron et al. 2019, Ellis et al. 2021, Miller-Cotto & Byrnes 2020, Schmitt et al. 2017) and in terms of the population investigated (only aggregate associations across the sample were reported rather than a deep investigation into subgroups). We hope further studies unpack these further questions.

Conclusion and future directions

Despite these limitations, results from the present investigation expand our understanding of the process by which math skills develop in early elementary grades. Results reproduce findings of substantial rank-order stability in mathematical skills across early elementary grades. These findings also support extant empirical and theoretical research that suggests that students with higher levels of EF enter school with higher mathematical skills on average than their peers, and also develop mathematical skills at a faster rate over subsequent years, which might in turn lead to an emergence or widening of already-present achievement gaps in math. However, the results from the present study suggest that students who enter school with low levels of mathematical skills but with high cognitive regulatory capacities might be able to catch up with their peers who enter school with greater mathematical skill.

These findings warrant further research. The role of EF as a moderator of growth in mathematical skills is certainly interesting, though the mechanism underlying this relation is unclear. Indeed, it is possible that children with higher EF skills are better able to direct attention to characteristics of instruction, inhibit irrelevant stimuli in classrooms, or recruit and test problem-solving strategies. However, additional research is necessary to shed light on the specific cognitive mechanisms that underlie the rate of development of mathematical skills. Importantly, given the findings on rank-order stability in math achievement over time, further research is needed to better understand the likelihood and predictors of placing children on different math trajectories over time in order to disrupt rank-order stability in math skills across elementary school.

Data availability statement

The data that support the findings of this study are openly available from the National Center for Education Statistics at https://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2017286.

Uncited references

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CRediT authorship contribution statement

Andrew D. Ribner : Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Sammy F. Ahmed :** Writing – review & editing. **Dana Miller-Cotto :** Writing – review & editing. **Alexa Ellis :** Writing – review & editing.

Data availability

data are publicly available through the US National Center for Education Statistics.

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