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The longitudinal contributions of preschool executive functions and early math abilities to arithmetic skills in elementary school☆☆,☆

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A R T I C L E I N F O

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A B S T R A C T

Executive functions (EFs) are linked to children's overall math performance, although few studies have considered the joint role of prior math abilities for specific math subskills, such as arithmetic. The current study examined the longitudinal contributions of preschool EFs and early math abilities to children's accuracy and reaction time on arithmetic problems. Two hundred and eighty-three children completed EF and numeracy assessments at 5.25 years old. Children completed an arithmetic problem task in first ($M_{age} = 7.14$), second ($M_{age} = 8.09$), and third grade ($M_{age} = 9.08$). Results indicated that preschool EFs and math abilities are uniquely linked to children's accuracy and reaction time at age 7, whereas preschool EFs alone continue to predict accuracy at age 8 and reaction time at age 9, even after accounting for intervening arithmetic performance. The study highlights the sustained, unique importance of early EFs for children's arithmetic acquisition.

Executive functions (EFs), cognitive skills that support regulation of attention and behavior, have consistently been associated with children's math skills (Clements et al., 2016; Purpura et al., 2017). The existing literature has largely focused on links between children's EFs and overall math achievement on standardized tests, which do not differentiate between the various components of children's mathematical abilities (Cragg & Gilmore, 2014). Arithmetic skills, such as addition and subtraction, are specific math skills that are vital to young children's math development (Purpura & Lonigan, 2013) and lay the foundation for children's subsequent development of more complex mathematics skills (Casey et al., 2015; Geary et al., 2012; Lee et al., 2018; Pongsakdi et al., 2020). While formal arithmetic skills are usually not taught until elementary school within the United States, children develop precursory numeracy skills, such as quantity discrimination, counting, and the understanding of cardinality, during the toddler and preschool periods

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(Starkey et al., 2004). Given the importance of arithmetic fluency for future math achievement (Casey et al., 2015), it is important to understand the early cognitive processes that aid in arithmetic skill development to better support children's educational trajectories.

While research highlights the associations between EFs and children's arithmetic skills (Michel et al., 2020; Viterbori et al., 2015), what is currently missing from the literature is knowledge of how early EFs and math abilities uniquely contribute to children's arithmetic fluency in elementary school. We aim to further the literature by examining how early EFs and math abilities not only relate to children's accuracy on arithmetic problems, but also to their *speed* on arithmetic problems, given the foundational importance of quick and accurate responses on arithmetic problems for children's continued math success (Carr & Alexeev, 2011; Geary, 2011). Specifically, the current study focuses on the longitudinal and unique relations of preschool EFs and math abilities to children's arithmetic fluency, as indexed by accuracy and reaction time (RT), on intermixed addition and subtraction problems, across first, second, and third grade.

1. Executive functions

EFs support children's regulation of their attention and behavior and comprise three core components – inhibitory control (controlling attention, behavior, and thoughts, resisting impulses), working memory (mentally manipulating information), and cognitive flexibility (flexibly changing or adjusting perspectives or rules; Diamond, 2013). Existing literature has generally emphasized a unitary conceptualization of EFs from three- to six-years of age (Carlson et al., 2014; Wiebe et al., 2011; Willoughby et al., 2012), although other studies have found a two-factor structure of preschool EF consisting of working memory and inhibitory control (Lerner & Lonigan, 2014; Miller et al., 2012; Simanowski & Krajewski, 2019). Indeed, a systematic review indicated that, although a one-factor solution is most common, this often is due to non-convergence of two-factor solutions. These authors argued that differences in the structure of EFs in early childhood are likely attributed to differences in EF task batteries, such as the type and number of EF tasks administered to young children (Karr et al., 2018).

Several studies evidence the interrelated, longitudinal links between EFs and math achievement (Miller-Cotto & Byrnes, 2020; Schmitt et al., 2017; Welsh et al., 2010). In preschool, EFs and math are thought to be bidirectionally associated with one another (Schmitt et al., 2017; Welsh et al., 2010). For example, Welsh et al. (2010) found that preschool EFs and numeracy skills at the beginning of the school year are both longitudinally and uniquely linked to preschool EFs and numeracy skills at the end of the school year. However, the strongest links are from EFs to math achievement (Coolen et al., 2021; Ellis et al., 2021), especially as children move into kindergarten (Fuhs et al., 2014; Schmitt et al., 2017). For instance, Schmitt et al. (2017) found that EFs and math skills were reciprocally related to one another from preschool to the beginning of kindergarten. By the end of kindergarten, only preschool EFs were associated with growth in math skills. Furthermore, EFs account for a large proportion of the variance in children's math performance even after controlling for related skills (i.e., IQ, processing speed, and reading skills) and demographic covariates (Bull & Scerif, 2001; Raghubar et al., 2010; Ribner et al., 2017). In one study, researchers found that EFs measured at four years accounted for 30 % of children's overall math achievement at age six, after controlling for socioeconomic status (Clark et al., 2010). Another study found that EFs predicted 43 % of the variance in children's general math performance, over and above children's spatial skills (Verdine et al., 2014).

While this literature reveals that EFs account for a large proportion of variance in children's overall math performance, most of this work has characterized mathematics achievement using standardized tests that incorporate multiple mathematics skills, with limited items assessing each type of skill. More refined, longitudinal assessments of specific subskills may help to clarify how early EF supports children's dynamic acquisition of mathematics. For example, EFs may be especially relevant in the context of intermixed arithmetic problems, where children may need to flexibly shift between operations and strategies (Bull & Lee, 2014). A comprehensive understanding of the role of early EF in children's math acquisition therefore requires attention both to specific components of math and the developmental timing of these associations.

Given the need to parse the contributions of EFs to specific math skills (Cragg & Gilmore, 2014), research has begun to examine the associations between EFs and arithmetic skills such as addition, subtraction, multiplication, and division (Bellon et al., 2019; Espy et al., 2004; Michel et al., 2020; Moll et al., 2015; Viterbori et al., 2015). One study found that performance on EF tasks was significantly correlated with higher accuracy on addition tasks in second grade (M_{age} = 7 years, 11 months; Bellon et al., 2019). Furthermore, results from longitudinal studies indicate that EFs measured at ages four- and six-years-old are associated with children's arithmetic skills over and above fine motor skills (Michel et al., 2020), fluid intelligence, and family demographics (Viterbori et al., 2015) into elementary school. Preschool EFs play a role in fact retrieval in addition and subtraction problems, as well as in accurate problem-solving on arithmetic word problems into early elementary school (Viterbori et al., 2015). While these studies indicate that EFs are linked to children's long-term accuracy in arithmetic problems, they did not account for children's earlier math abilities, possibly overestimating the associations between EFs and later arithmetic skills. Moreover, many of these studies examined accuracy while overlooking children's speed during these problems, despite evidence that slower retrieval of mathematics facts is an especially salient predictor of mathematics difficulties (Geary et al., 2012).

1.1. Early math abilities

Existing literature documents the substantial continuity between early math skills and math achievement in elementary school (Duncan et al., 2007; Jordan et al., 2006; Jordan et al., 2009). Early numeracy skills, such as quantity discrimination (i.e., the ability to correctly distinguish set sizes and/or numbers) and counting, are important building blocks for future math achievement (Aunola et al., 2004; Jordan et al., 2006; Lembke & Foegen, 2009), including arithmetic skills (Rittle-Johnson et al., 2017). Furthermore, research highlights the links between early numbering abilities and children's speed in correctly identifying answers. For example, Major et al. (2017) found that numeracy skills, as assessed by the Test of Early Math Ability (TEMA-2) at age five, predicted quicker RT on addition problem-solving one year later, even when controlling for children's concurrent ability to enumerate sets of items, magnitude comparison skills, and general cognitive abilities (i.e., working memory and non-verbal IQ). Importantly, the predictive value of early math skills holds long-term, as research highlights how numeracy abilities (i.e., magnitude comparison and counting) measured at age four predict overall math performance into later elementary grades (Rittle-Johnson et al., 2017) and into high school (Watts et al., 2014).

1.2. Unique contributions of EFs and early math abilities for future math

To better understand how to support children's arithmetic skills in elementary school, it is important to explore the unique contributions of both early EFs and math abilities. When examining children's overall math achievement, findings indicate that both EF and math abilities at ages four and five years uniquely contribute to math outcomes in second and fifth grade (Fuhs et al., 2014; Ribner et al., 2017). Furthermore, both EFs and prior math are uniquely predictive of children's addition skills. For example, one study showed that preschoolers' symbolic magnitude comparison skills, number line estimation skills, and EFs each uniquely predicted addition skills three and a half months later (Scalise & Ramani, 2021). This pattern seems to hold into elementary school, as cross-sectional work finds that both EFs and math abilities, as measured by symbolic numerical magnitude, are uniquely linked to second-grade children's addition skills (M_{age} = 7 years, 11 months; Bellon et al., 2019).

It is important to evaluate the potentially dynamic predictive relevance of early mathematics skills and EFs for children's arithmetic fluency over time. While many studies have narrowly focused on children's arithmetic accuracy (Michel et al., 2020; Viterbori et al., 2015), examining speed as a developmental outcome is valuable for children's arithmetic trajectory and overall math achievement. Children who are quick in completing arithmetic problems have more cognitive capacity (i.e., working memory capacity) to focus on other aspects of problem-solving, which contributes to their strategy use and math achievement (Carr & Alexeev, 2011). Moreover, speed may indicate a developmental trend towards using retrieval or cognitive-based strategies rather than manipulative-based strategies (e.g., counting), which is adaptive for children's developmental trajectories of math strategies (Shrager & Siegler, 1998). Adaptive application of different strategies is especially relevant for children's math achievement as arithmetic is foundational for multi-step problems, where children may need to use various strategies to problem-solve as well as keep in mind which step that they are at.

While there is some theoretical and empirical evidence to suggest that both EF and math uniquely contribute to addition skills, it is important to extend this research to examine intermixed addition and subtraction problems. For instance, blocked problems contain problem sets that use the same skills or concepts which are quite common in mathematics textbooks, while intermixed problem contain sets with various skills or concepts (Rohrer et al., 2020). With intermixed problems, children must recognize cues (such as the specific sign attached to an arithmetic problem), and flexibly switch strategies according to those cues while inhibiting the use of a previous strategy. Further, young children tend to use a myriad of different strategies when solving for an answer (Farrington-Flint et al., 2009) and learn to adaptively select strategies that work for them over time (Shrager & Siegler, 1998). As such, elementary-school children must be able to inhibit irrelevant strategies as well as actively maintain and update relevant information when solving arithmetic problems (Bellon et al., 2019). Intermixed arithmetic problems are likely to place strong demand on EFs, particularly during the early phases of learning when students are less able to draw on rote recall (retrieval). As children transition into upper elementary school, their capacities to shift between addition and subtraction quickly and effectively are important for their abilities to answer multi-part word problems and algebraic problems. Indeed, research indicates that EF tasks are significantly and moderately correlated with accuracy on multiple step math word problems in elementary school (*r*s range from .23 to .52), providing some evidence that EFs help coordinate resources relevant for multiple step problems (Agostino et al., 2010).

1.3. Current study

Although there are well-documented links between children's early EF and mathematics skills, there is a need for studies that examine the developmentally dynamic contributions of early EF and early mathematics skills to children's acquisition of specific math subskills, such as fluency in solving intermixed arithmetic problems longitudinally into elementary school. This study examined whether preschool EFs and math abilities uniquely contribute to children's accuracy and RT in solving arithmetic problems in elementary school, after controlling for socio-demographic covariates. Leveraging longitudinal data from preschool (5.25 years) to third grade (M_{age} = 9.08 years), we used a socioeconomically diverse sample to explore the direct and mediating associations between directly-assessed EFs and math abilities in preschool, and children's accuracy and RT in solving arithmetic problems across three elementary school timepoints – first, second, and third grade. We hypothesized that preschool EFs and math abilities would uniquely and additively predict accuracy and RT on arithmetic problems, such that preschool EF and math skills would be linked to arithmetic fluency in first grade with cascading effects on children's arithmetic fluency in second and third grade via performance in first grade. As such, we believed that preschool EFs and math abilities would contribute to higher accuracy and quicker speed on arithmetic problems as children moved through elementary school.

2. Method

2.1. Participants

The preschool sample was taken from Preschool Problem Solving Study (Espy, 2016). In this sample, families with typically developing preschool children were recruited from two large cities in the Midwestern United States through birth announcements, fliers distributed to doctors' offices, preschools, and health departments, and by word of mouth. Exclusion criteria included any delays in language development, diagnosed learning or behavioral disorders, English as a second language for families, or a planned move during the study. This preschool study included a lagged, cohort-sequential design with most children enrolled at 3 years; 0 months and followed every 9 months until 5 years; 3 months ($n = 228$). A subset of children was enrolled at intervening age points ($n = 50$) for a total sample of 388 preschool children. Following this, additional funding was obtained, and more children were recruited into the study for a larger sample size ($n = 480$). At each timepoint, preschoolers visited the lab with an adult within two weeks of the specified age for that timepoint. For the current study, we used data from the 5 years; 3 months timepoint, as the sample was largest at this timepoint ($n = 480$), and a standardized math assessment was administered at this timepoint.

Families from only one of the two sites for original preschool study were asked to participate in the elementary school follow-up phase that began in first grade (Nelson et al., 2017). Ethics approval for the preschool and elementary school samples came from the institutional review board at the University of Nebraska-Lincoln and the study was conducted in accordance with APA ethical guidelines. Of the 313 preschoolers eligible to participate in the follow-up phase, 285 children had elementary school data. Two of these children were dropped from the sample as they repeated first grade twice. Approximately half of the children were boys (48 %) and just over a quarter of the children identified as racial/ethnic minorities (28 %). Of these 283 children, 210 children had assessment data from first grade ($M_{age} = 7.14$, $SD_{age} = 0.34$), 250 children had assessment data from second grade ($M_{age} = 8.09$, $SD_{age} = 0.36$), and 166 children had assessment data from third grade ($M_{age} = 9.08$, $SD_{age} = 0.36$). The lower rate in first grade was due to a lapse in funding; once funding to follow the children into elementary school was obtained, a portion of children had already begun second grade and were instead assessed at that time point. Similarly, funding for the follow-up study ended before many of the children reached third grade.

2.2. Procedure

At the preschool (5.25 years) assessment point, children attended a lab visit with a primary caregiver (parent) who completed questionnaires while the child completed a battery of child-friendly EF tasks and a standardized math measure. The tasks were administered by trained research assistants and each visit lasted around two hours. After the session, the parent received compensation and the child received a toy. Similarly, in the elementary school grades, children attended a two-hour lab assessment in the spring of each school year that included various measures, including the arithmetic task described below.

2.3. Measures

2.3.1. Preschool EFs

The nine EF tasks included Nine Boxes (Diamond et al., 1997), Delayed Alternation (Espy et al., 1999), Nebraska Barnyard (Hughes et al., 1998), Big-Little Stroop (Kochanska et al., 2000), Go/No-Go (Simpson & Riggs, 2006), Shape School – inhibit and switching conditions (Espy, 1997), modified Snack Delay (Kochanska et al., 2000), and the Trails – switching condition (Espy & Cwik, 2004) tasks. Three tasks measured working memory (i.e., Nine Boxes, Delayed Alternation, and Nebraska Barnyard), four tasks measured inhibitory control (i.e., Big-Little Stroop, Go/No-Go, Shape school – inhibit, and modified Snack delay), and two tasks measured cognitive flexibility (i.e., Shape School – switching and Trails – switching). More detailed information is provided in the monograph (James et al., 2016).

EF task scores that deviated more than 3 standard deviations (SDs) from the average ($n = 5$) were winsorized to the next highest score. In the sample of 313 preschool children, confirmatory factor analyses (CFA) revealed a unitary EF construct for the nine tasks at the same timepoint (Nelson et al., 2017). We ran a one-factor CFA for subset of 283 preschool children who were followed into elementary school and found adequate fit (CFI =.900, RMSEA =.055, 95 % confidence interval = [.030,.079], SRMR = 0.047). See Appendix A for standardized factor loadings, standard errors, and *p*-values. Based on recent measurement work focused on how to best measure EFs in early childhood (Camerota et al., 2020; Rhemtulla et al., 2020), we standardized and averaged the nine EF tasks. The creation of a composite score involves use of the full variance across the nine tasks, rather than the small portion of shared variance across the tasks which have relatively low inter-task correlations (Willoughby et al., 2012). Inter-task correlations are in Appendix B. Compared to the use of a latent EF variable, models using composite EF measures demonstrate better longitudinal prediction of academic outcomes and more reasonable and appropriate estimates of cross-time stability that align with stability estimates across single tasks (Camerota et al., 2020). Not only is a composite score better for replicability purposes, as factor loadings will change across samples, it also is a more conservative way to measure EF as it does not overweight the more sensitive tasks. The use of the composite score was a deviation from our pre-registration, in which we had planned to use principal components analysis (PCA) to create a composite score.

2.3.2. Preschool Math Ability

The Test of Early Math Ability – Third Edition (TEMA-3) (Ginsburg & Baroody, 2003) is a standardized measure of numeracy skills in early childhood, including formal (e.g., written representation of numbers) and informal (e.g., numbering and calculation) mathematical skills. There are 72 items, ranging from counting to simple division, and the TEMA-3 covers six domains: numbering skills, number-comparison facility, numeral literacy, proficiency in number facts, calculation skills, and understanding of concepts. During testing, a basal (i.e., five consecutive items scored as correct) must be established and the test ends when a ceiling is reached (i.e., five consecutive items scored as incorrect). Each item is scored as correct or incorrect. The dataset indicated strong reliability (α = .93). The children's standard score, also referred to as the *math ability score*, was used.

2.3.3. Elementary school arithmetic problems

The Math Problems Task (Farrington-Flint et al., 2009) was administered to assess children's accuracy and RT when completing arithmetic problems. The task was administered by a trained research assessor using E-Prime 2. During this task, children were video-recorded so that research assistants could later code accuracy and RT using Noldus Observer Video-Pro 5.0.31 (Noldus et al., 2000). On the computer screen, children were shown 40 arithmetic problems and asked to verbally answer the problem. The examiner pressed the space bar to present each problem successively and then waited for the child to make a response before advancing the screen. There was an equal number of 20 addition and 20 subtraction problems presented in a standard sequence to ensure longitudinal continuity of the assessments within children. For both the addition and subtraction problems, half of the problems had sums that were less than 10 and the other half had sums that were between 10 and 20. The sum problems were arranged so that some problems had the larger number first (e.g., 14 + 4) while others had the smaller number first (e.g., 3 + 16). There were 17 single-digit (e.g., 8 – 2 = 6; 3 + 6 = 9), 23 double-digit (e.g., 14 + 4 = 18; 19–4 = 5) problems, and 21 instances in which the problems switched from a different sign type (e.g., problem switched from addition to subtraction and vice versa).

Children's accuracy was calculated as the percentage of arithmetic problems they answered correctly. RT trials were coded in Noldus by carefully finding the earliest frame where children began to articulate their verbal response relative to the first frame of the trial where the problem was visible. Accurate trial RTs were averaged to obtain children's overall RT. The dataset indicated strong internal reliability for children's accuracy in first (α = .92), second (α = .86), and third grade (α = .72) as well as children's RT in first (α = .94), second (α = .92), and third grade (α = .94). Using the Pearson correlation coefficient, inter-rater reliability was calculated across 236 double-coded trials ($r = .98$). We excluded RT trials if individual trials were above one minute to remove any trials in which children were not paying attention or not actively trying to solve the problem. We winsorized children's average RTs that deviated more than 3 standard deviations (SDs) from the group average of each grade ($n = 8$) (Vanbinst et al., 2012).

2.3.4. Covariates

Covariates included child gender (1 = *male*), child race/ethnicity status (1 = *racial/ethnic minority*), household total income, and years of maternal education. Parents reported on these demographic variables at the preschool visit. Child gender and race/ethnicity status were included as covariates to control for any potential gender and racial/ethnic differences in preschoolers' EF and math performances (Mileva-Seitz et al., 2015; Nesbitt et al., 2013). Additionally, household income and years of maternal education were included as they are both strongly associated with EFs (Raver et al., 2013) and academic achievement (Lurie et al., 2021).

2.3.5. Analytic plan

Data were cleaned and scored in SPSS (Version 27.1; IBM Corp, 2020) and Stata (Version 16.1; StataCorp, 2017), and structural equation modeling was run in MPLUS (Version 7.3; Muthén & Muthén, 2014). Pre-registered analyses are available through the Open Science Framework website (https://doi.org/10.17605/OSF.IO/K4XCG). Given that the data were drawn from a larger study, the pre-registration was written after data collection occurred. Data collection and analyses were completed by different authors – the two authors who completed analyses were not part of data collection team for this study.

As our primary analyses, we ran two models to examine accuracy and RT as separate outcomes. We examined the direct effects of both preschool EFs and math on children's accuracy/RT on the math task in first, second, and third grade, while also including direct pathways to account for longitudinal continuity in arithmetic skills across the grades. We then estimated a serial mediation model to examine the indirect effects of preschool EFs and prior math abilities on arithmetic accuracy and RT in second and third grade via first and second grade (Ahmed et al., 2021). First, we examined the indirect effects of preschool EFs to second-grade accuracy/RT via first-grade accuracy/RT, preschool EFs to third grade accuracy/RT via second-grade accuracy/RT, and preschool EFs to third-grade accuracy/RT via first- and second-grade accuracy/RT. Second, we examined the indirect effects of preschool math to second-grade accuracy/RT via first-grade accuracy/RT and preschool math to third-grade accuracy/RT via first- and second-grade accuracy/RT.

Child gender, child race/ethnicity minority status, years of maternal education, and log-transformed household income were included in the models as covariates. We covaried the demographic covariates with one another as well as preschool EFs and prior math abilities. To test direct effects, we used a robust estimator (ESTIMATOR = MLR) due to the non-normality of the arithmetic accuracy data. To test indirect effects, we used the MODEL INDIRECT command and a bootstrapping approach (Shrout & Bolger, 2002). We performed a nonparametric resampling method with 5000 resamples to derive 95 % confidence intervals to interpret indirect effects of children's preschool EF and prior math on second- and third-grade outcomes through first- and second-grade outcomes.

2.3.6. Alignment with and deviations from the pre-registration

The original pre-registered analyses included children's 'switching accuracy' as an outcome, where 'switching accuracy' was indexed by children's accuracy across the 21 problems that switched from a different sign type (e.g., children's accuracy on a subtraction problem when the problem before used addition or vice versa). Identical to the primary models presented in this study, we examined the direct effects of both preschool EFs and math on children's switching accuracy on the math task in first, second, and third grade, while also including direct pathways to account for longitudinal continuity in arithmetic skills across the grades and accounting for children's gender, child race/ethnicity minority status, family household income, and years of maternal education. The model would not converge using the family household income variable, due to the skewness of this variable, so we log transformed the variable using the natural logarithm. We evaluated model fit by utilizing the Comparative Fit Index (CFI; values $\geq$.95 indicate excellent model fit; Bentler, 1990), Root Mean Square Error of Approximation (RMSEA; values ≤ 0.05 indicate excellent model fit; (Browne & Cudeck, 1993), and Standard Root Mean Residual (SRMR; values ≤ 0.05 indicate excellent model fit; Hu & Bentler, 1999). The model fit was strong, $\chi^2(df = 13) = 10.504$, $p = .652$, RMSEA < 0.001, CFI $= 1.000$, SRMR $= 0.027$.

We believed that it was important to update our analyses to examine accuracy across all trials, rather than to only examine accuracy on the 21 switch trials. Many EF tasks, such as the Dimensional Change Card Sort Task (DCCS), use mixed trials to measure EFs. For instance, DCCS begins by sorting cards by color and then sorting cards by shape. After six trials of each type of sorting, children advance to the next phase where they must sort cards by shape or by color while adhering to the rule (i.e., sort by color when there is a black box around the image on the card and sort by shape when there is no black box around the image on the card). Accuracy across all of the intermixed color and shape trials are used to assess children's EFs, because the cognitive load of switching between different rules is present for all trials, not just those that require a switch. As such, we updated analyses from the pre-registration to reflect this change in our outcome variable. We included the original pre-registered analyses with just the 21 switch trials in Appendix C and the results are substantially similar to the primary analyses used in the paper with accuracy across all 40 trials.

Updated pre-registered analyses also included the use of children's RT. The pre-registration indicated that RT trials were excluded for trials that deviated more than 3 SDs from the child's mean accurate RT across all trials. We deviated from the pre-registration by removing this exclusion criterion after examining the data, as we found that this would exclude children's slower RT trials for those who performed quickly on the task overall as well as excluding children's RT trials for more challenging questions when they would be expected to slow down (e.g., $17 - 11 = 6$). As stated above, we also removed two children from the sample for repeating a grade twice, which was not originally included in our pre-registration.

2.3.7. Missing data

All missing data was addressed through full information maximum likelihood (FIML) estimation which utilizes the available data set of the 283 children to create the parameter estimates and does not discount incomplete cases (Enders, 2011). We retained all children in the sample who had elementary school data. Ten children were missing all nine EF tasks, and 20 children were missing the preschool math score. There were an additional ten children who were missing at least one EF task – nine children had one missing EF task and one child had two missing EF tasks. For children with any missing demographic data at the 5 years, 3 months timepoint, demographics were obtained from the first timepoint that they joined the study. There were complete cases for children's gender, racial/ethnic minority status, and maternal education. One family listed their yearly household income as zero; we replaced this as missing. We then examined missing data patterns across children's elementary school years. We found that across three elementary school timepoints, 99 children had data from all three timepoints, 145 children had data from two timepoints, and 39 children had data from only one elementary school timepoint.

3. Results

3.1. Descriptive statistics and bivariate correlations

Descriptive statistics and bivariate correlations are shown in Tables 1 and 2, respectively. Children's preschool math scores ($M = 97.22$, $SD = 15.10$) on the TEMA-3 were similar to the overall distribution of scores in the United States ($M = 100$, $SD = 15$). Children performed increasingly well on arithmetic problems over time, completing the task with an average accuracy of 73 % in first grade, 88 % in second grade, and 93 % in third grade. The range in performance was 10–100 % in first grade, 15–100 % in second grade, and 63–100 % in third grade. Two-way comparisons were conducted to examine potential differences between performance across each

Table 1
Descriptive Statistics.

	M/%	*SD*	Min	Max	Skewness	Kurtosis	*N*
Preschool EF composite	0.01	0.50	-1.57	1.10	-0.87	3.93	273
Preschool math score	97.22	15.10	64	135	0.26	2.30	263
Male child	47 %		0	1	0.11	1.01	283
Child racial/ethnic minority	28 %		0	1	0.95	1.89	283
Household income	$51,693	$35,911	$3516	$194,000	1.21	4.46	282
Years of maternal education	14.48	2.24	8	21	0.23	3.33	283
1st grade accuracy	73 %	0.21	0.10	1	-0.97	3.57	210
2nd grade accuracy	88 %	0.13	0.15	1	-2.01	8.38	250
3rd grade accuracy	93 %	0.07	0.63	1	-1.73	6.49	166
1st grade reaction time	8.18	3.57	1.71	19.95	0.92	3.98	210
2nd grade reaction time	5.03	2.40	1.20	12.71	0.96	3.98	250
3rd grade reaction time	3.73	2.12	1.00	10.54	1.14	3.69	166

Note. M = mean, SD = standard deviation, min = minimum of range, max = maximum of range.

Table 2
Bivariate correlations.

	1	2	3	4	5	6	7	8	9	10	11
1. Preschool EF composite											
2. Preschool math score	.45***										
3. Male child	-.13*	-.02									
4. Racial/ethnic minority	-.17**	-.09	-.05								
5. Household income	.23***	.25***	.05	-.28***							
6. Years of maternal education	.26***	.28***	-.09	-.23***	.49***						
7. 1st grade accuracy	.28***	.41***	.04	-.16*	.19**	.21**					
8. 2nd grade accuracy	.34***	.35***	.02	-.06	.14*	.18**	.56***				
9. 3rd grade accuracy	.31***	.33***	.03	-.14	.14	.09	.38***	.64***			
10. 1st grade reaction time	-.04	-.32***	-.12	.13	-.12	-.10	-.22**	-.29***	-.32**		
11. 2nd grade reacion time	-.15*	-.33***	-.11	.13*	-.21**	-.19**	-.40***	-.42***	-.43***	.64***	
12. 3rd grade reaction time	-.30***	-.41***	-.15	.12	-.22**	-.15*	-.43***	-.57***	-.45***	.54***	.74***

*$p < .05$, **$p < .01$, ***$p < .001$.

grade. Results indicated significant differences between performance in first and second grade ($t(192) = -12.88, p < .001$), second and third grade ($t(145) = -5.77, p < .001$), and first and third grade ($t(102) = -9.83, p < .001$). Children also became increasingly fast on the arithmetic problems – average RTs were 8.18 seconds in first grade, 5.03 seconds in second grade, and 3.73 seconds in third grade. Results indicated significant differences between RTs in first and second grade ($t(192) = 15.87$, $p < .001$), second and third grade ($t(145) = 8.20$, $p < .001$), and first and third grade ($t(102) = 13.77$, $p < .001$).

Household income and maternal education were both positively associated with preschool EF and math scores, indicating that children from families with higher annual household income and more years of maternal education performed better on EF tasks and the TEMA-3, on average. Moreover, boys performed slightly worse than girls on the EF tasks but showed no significant differences in preschool math scores. Children's racial/ethnic minority status was significantly and negatively correlated with EF scores, household income, maternal education, and accuracy in first grade as well as positively correlated with RT in second grade. EF and preschool math scores were positively correlated with one another, and both were positively correlated with accuracy on the arithmetic task across first, second, and third grade. Preschool math scores, but not EF scores, were significantly correlated with faster RT in first grade. Both preschool EF and math scores were significantly correlated with faster RTs in second and third grade. As expected, accuracy scores across first, second, and third grade were all highly correlated with one another (*r*s range from .38 to .64) and RTs across first, second, and third grade were all highly correlated with one another (*r*s range from .54 to .74). Generally, higher accuracy was linked to faster RTs across all grades (*r*s range from −.22 to −.57).

3.1.1. *Structural equation models*

Structural equation modeling was used to examine the associations between preschool EFs, preschool math, and arithmetic performance across first, second, and third grade, while controlling for family demographics. All standardized path coefficients for

Table 3
Structural equation models standardized path coefficients.

	Accuracy			Reaction time		
Direct pathways	β	SE	*p*-value	β	SE	*p*-value
1st grade						
Preschool EF composite	0.171	0.067	.011	0.120	0.069	.082
Preschool math score	0.373	0.058	< .001	-0.386	0.064	< .001
2nd grade						
Preschool EF composite	0.152	0.066	.022	-0.082	0.060	.172
Preschool math score	0.083	0.062	.178	-0.094	0.060	.116
First grade outcome	0.537	0.064	< .001	0.613	0.060	< .001
3rd grade						
Preschool EF composite	0.048	0.067	.472	-0.123	0.061	.044
Preschool math score	0.058	0.080	.473	-0.107	0.080	.182
Second grade outcome	0.678	0.068	< .001	0.681	0.054	< .001
Covariance						
EF with math	0.446	0.049	< .001	0.447	0.049	< .001
EF with male child	-0.129	0.059	.028	-0.130	0.059	.028
EF with child racial/ethnic minority	-0.172	0.063	.006	-0.171	0.063	.007
EF with income	0.287	0.058	< .001	0.287	0.058	< .001
EF with maternal education	0.257	0.054	< .001	0.258	0.054	< .001
Math with male child	-0.008	0.061	.898	-0.011	0.061	.864
Math with child racial/ethnic minority	-0.098	0.063	.123	-0.089	0.063	.156
Math with income	0.241	0.055	< .001	0.241	0.055	< .001
Math with maternal education	0.271	0.055	< .001	0.269	0.055	< .001

*$p < .05$, **$p < .01$, ***$p < .001$.

children's accuracy and RTs are reported in Table 3 and represented in Figs. 1 and 2, respectively.

3.1.2. Accuracy on arithmetic problems

Estimation of the model examining accuracy provided support for strong global fit, $\chi^2(13) = 6.195$, $p = .939$, RMSEA < 0.001, 90 % confidence interval [0.000, 0.013], CFI = 1.000, and SRMR = 0.024. In first grade, both preschool EFs and math skills were significantly linked to children's accuracy in arithmetic problems ($\beta = 0.171$, $p = .011$; $\beta = 0.373$, $p < .001$, respectively). In second grade, preschool EFs were significantly linked to accuracy ($\beta = 0.152$, $p = .022$), while preschool math not significantly linked to accuracy ($\beta = 0.083$, $p = .178$), after accounting for the longitudinal continuity in first grade to second grade accuracy. In third grade, neither preschool EFs nor math were significantly linked to accuracy ($\beta = 0.048$, $p = .472$; $\beta = 0.058$, $p = .473$, respectively). As expected, there was strong longitudinal continuity in children's accuracy scores: accuracy in first grade was linked to accuracy in second grade ($\beta = 0.537$, $p < .001$) and accuracy in second grade was linked to accuracy in third grade ($\beta = 0.678$, $p < .001$). All covariates were significantly covaried with preschool EFs, whereas only income and maternal education were significantly covaried with preschool math.

Next, we examined the indirect effects, reported in Table 4. Indirect effects demonstrated that preschool EFs and preschool math each predicted second-grade accuracy through first-grade performance (95 % confidence intervals (CIs): [0.391, 4.810]; [0.101, 0.250]; respectively). Further, preschool EFs and math predicted third-grade accuracy through first- and second-grade performance (95 % CIs: [0.147, 2.062]; [0.037, 0.105]; respectively). Last, preschool EFs predicted third-grade accuracy through second-grade accuracy (95 % CIs: [0.138, 3.282]). As indicated by the R^2 values, the tested model explained 23 % of the variance in children's accuracy scores in first grade, 43 % of the variance of accuracy scores in second grade, and 52 % of the variance of accuracy scores in third grade.

3.1.3. Speed on arithmetic problems

Estimation of the model examining RT provided support for a strong global fit, $\chi^2(13) = 15.938$, $p = .253$, RMSEA = 0.028, 90 % confidence interval [0.000, 0.069], CFI = 0.992, and SRMR = 0.049. In first grade, preschool math was significantly linked to children's faster RTs on arithmetic problems ($\beta = -0.386$, $p = <.001$), however, results indicated that preschool EFs were not significantly linked to children's RTs ($\beta = 0.120$, $p = .082$). In second grade, there were no significant links from preschool EFs and math to arithmetic RTs ($\beta = -0.082$, $p = .172$; $\beta = -0.094$, $p = .116$, respectively). Furthermore, in third grade, preschool math was not linked to RTs ($\beta = -0.107$, $p = .182$), however, results indicated that preschool EFs were significantly linked to faster RTs ($\beta = -0.123$, $p = .044$). Similar to accuracy, there was strong longitudinal continuity in RTs from first to second grade ($\beta = 0.613$, $p < .001$) and from second to third grade ($\beta = 0.681$, $p < .001$). All covariates were significantly covaried with preschool EFs, whereas income and maternal education were significantly covaried with preschool math.

Indirect effects demonstrated that preschool math predicted second-grade RT though first-grade RT (95 % CIs: [−0.056, −0.023]). However, preschool EFs did not predict second-grade RT through first-grade RT (95 % CIs: [−0.054, 0.797]). Further, preschool math predicted third-grade RTs through first- and second-grade RTs (95 % CIs: [−0.034, −0.013]), however, preschool EFs did not predict third-grade RTs through first- and second-grade RTs (95 % CIs: [−0.028, 0.485]. As indicated by the R^2, the tested model explained 12 % of the variance of RT performance in first grade, 44 % of the variance in second grade, and 58 % of the variance in third grade.

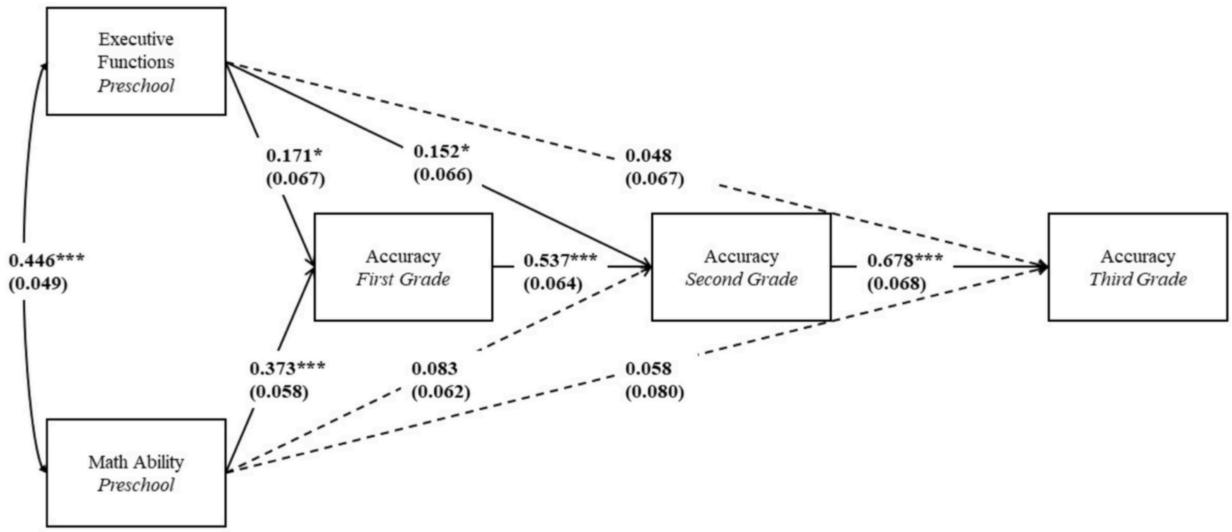

Fig. 1. Structural Equation Model for Preschool EF and Math Abilities Predicting Accuracy. Note. Path analyses demonstrating associations between preschool EFs, preschool math ability, and accuracy in first, second, and third grade. The model allowed for covariance between the preschool EFs and preschool math abilities. Standardized coefficients are presented. Path models do not show covariation between preschool EFs, math abilities, and demographic covariates. *$p < .05$, **$p < .01$, ***$p < .001$.

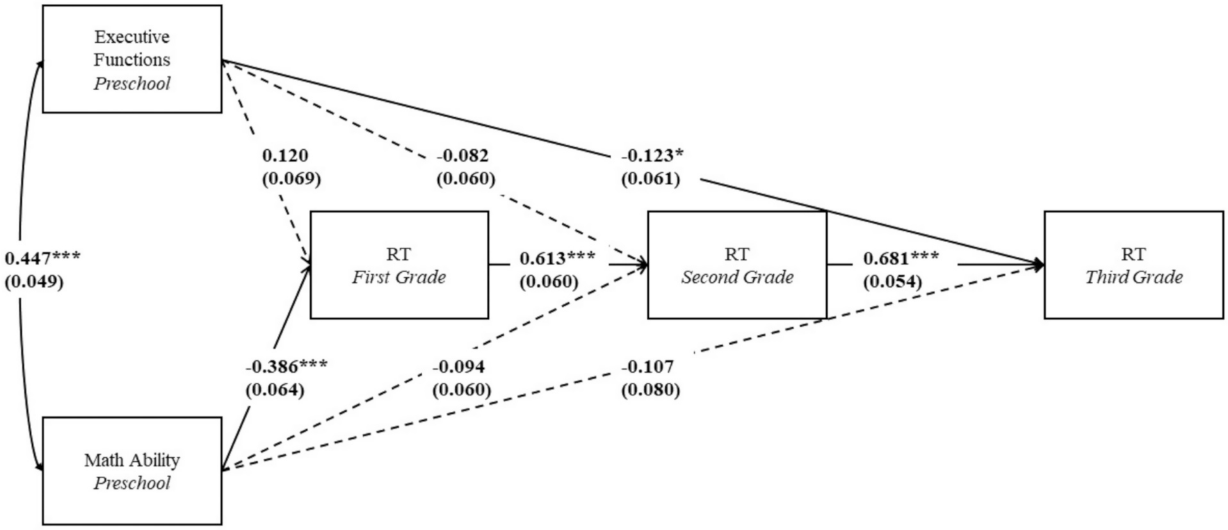

Fig. 2. Structural Equation Model for Preschool EF and Math Abilities Predicting RT. Note. Path analyses demonstrating associations between preschool EFs, preschool math ability, and RT in first, second, and third grade. The model allowed for covariance between the preschool EFs and preschool math ability. Standardized coefficients are presented. Path models do not show covariation between preschool EFs, math abilities, and demographic covariates. $*p < .05$, $**p < .01$, $***p < .001$.

Table 4
Indirect path coefficients and confidence intervals.

Indirect pathways	*β*	*b*	95% CI	Sig at α = .05
Accuracy				
Preschool EF → 1st grade accuracy → 2nd grade accuracy	0.092	2.414	0.391, 4.810	Yes
Preschool EF → 2nd grade accuracy→ 3rd grade accuracy	0.103	1.594	0.138, 3.282	Yes
Preschool EF → 1st arade accuracy → 2nd grade acuracy → 3rd grade accuracy	0.062	0.959	0.147, 2.062	Yes
Preschool math → 1st grade accuracy→ 2nd grade accuracy	0.200	0.172	0.101, 0.250	Yes
Preschool math → 1st grade accuracy → 2nd grade accuracy → 3rd grade accuracy	0.136	0.068	0.037, 0.105	Yes
Reaction time				
Preschool EF → 1st grade RT → 2nd grade RT	0.074	0.360	−0.054, 0.797	No
Preschool EF → 1st grade RT → 2nd grade RT → 3rd grade RT	0.050	0.213	−0.028, 0.485	No
Preschool math → 1st grade RT → 2nd grade RT	-0.237	-0.038	−0.056, −0.023	Yes
Preschool math → 1st grade RT → 2nd grade RT → 3rd grade RT	-0.161	-0.023	−0.034, −0.013	Yes

Note. EF = preschool executive function composite, Math = preschool math score, RT = reaction time, CI = Confidence Interval.

4. Discussion

This study demonstrated that preschool EF and math abilities portend children's arithmetic skills in early elementary school, specifically on a task assessing children's accuracy and RTs across intermixed addition and subtraction problems. We found that preschool EFs and math abilities each were uniquely predictive of children's accuracy on arithmetic problems in first grade, with cascading effects for accuracy on arithmetic problems in second and third grade. As children progressed into second grade, preschool EFs continued to predict accuracy in arithmetic problems into second grade independent of their indirect pathway via first grade accuracy. Furthermore, results indicated that preschool math abilities, but not EFs, related directly to children's RTs on arithmetic problems in first grade, with cascading effects into second and third grade. Interestingly, preschool EFs uniquely predicted quicker RTs in third grade independent of children's RTs in second grade. Thus, while early math abilities are important for supporting children's math outcomes as they transition into elementary school, EFs continued to show predictive relevance into third grade, even when accounting for early math abilities. Thus, EFs may provide children with the advantage of performing accurately and quickly by facilitating rapid selection of answers, switching of strategies, and focused attention to the problem at-hand.

4.1. *The importance of preschool math for arithmetic problems in first grade*

Existing literature highlights the importance of children's early number knowledge for future math learning (Duncan et al., 2007; Jordan et al., 2006; Jordan et al., 2009). As indicated by our results, early math abilities are important for both accuracy and speed in solving arithmetic problems in early elementary school. The TEMA assesses children's abilities to discriminate magnitude, as well as several counting concepts that emerge during early childhood, including children's understanding of cardinality, one-to-one correspondence, and the succession principle (i.e., the principle that each whole number is one more than the previous number) (Ginsburg & Baroody, 2003). All of these numeracy skills are fundamental to students' understanding of addition and subtraction. For instance, children need to understand the cardinal principle to understand how sets can be combined and parsed. Additionally, they need to become fluent in the succession principle to be able to compare numbers as well as use various arithmetic strategies, such as counting up from the largest number (e.g., the 'min' strategy). Young children employed this previously learned, basic counting and numerical knowledge, to solve the addition and subtraction problems more accurately and quickly. In the current study, the math problems task contained double-digit problems (e.g., 17–6 = 11), which may be difficult for first graders to retrieve from memory. For first-grade children who cannot retrieve double-digit problem answers from memory, they must rely on their prior math knowledge and strategies to correctly compute the answer. Supporting this, Malone et al. (2022) found that math specific skills (e.g., number knowledge and counting) at age five are associated with arithmetic skills at age six, when accounting for EFs. The current study also supports existing literature providing evidence on how early math abilities, as assessed by the TEMA, relate to children's problem-solving speed (Major et al., 2017).

Interestingly, as children progressed through elementary school, preschool math abilities were no longer directly related to their accuracy and speed on arithmetic problems and instead were linked to their arithmetic fluency via their performance in first grade. This aligns with research indicating that children move away from utilizing their prior math skills, such as the use of counting fingers or objects (Carr & Taasoobshirazi, 2017), to more retrieval-based strategies over time as they become better at problem-solving (Ashcraft, 1982, 1987). Furthermore, first-grade accuracy and speed on arithmetic problems mediated the pathway between prior math and later accuracy and speed on arithmetic problems. This result suggests that prior math abilities serve as building blocks that support children's arithmetic abilities, with cascading effects through early elementary school. As such, the results indicate that children rely on their previous math skills to be more accurate and faster in first grade. As children move through their schooling, they must be able to solve arithmetic problems more easily and quickly or they may be at-risk for falling behind their peers, given that addition and subtraction are foundational for the more complex math problems that they begin to encounter in second grade and beyond (Casey et al., 2015; Lee, Ng, & Bull, 2018; Pongsakdi et al., 2020).

4.2. EFs as a unique predictor of accuracy and RT on arithmetic problems

The current study supports the notion that EFs contribute to accuracy and speed on arithmetic problems in elementary school, after controlling for prior math abilities. These findings align with prior work suggesting that preschool EFs are strong predictors of math achievement well beyond early childhood (Bull & Lee, 2014; Fuhs et al., 2014; Ribner et al., 2017), while expanding this work to reveal changing relations over time. Specifically, there was a unique effect of preschool EFs on first-grade accuracy and second-grade accuracy, over and above preschool math abilities and the indirect effect via first-grade accuracy. As children start to rely less on their foundational math skills as they become more skilled in arithmetic, they may begin to rely more heavily on EF skills to mentally manipulating information and retrieve answers from memory (Fuhs et al., 2014). EFs may also support children's understanding of the inverse relationship between addition and subtraction problems, which is beneficial to accurately solving arithmetic skills. For example, the math problems task contained a handful of inverse problems (e.g., 8 – 2 = 6; 2 + 6 = 8). If children can understand these inverse relationships, they may be capable of retrieving the answer from memory to be accurate in their response rather than trying to utilize their math skills to solve the problems. Furthermore, research supports that EFs significantly contribute to children's strategy selection skills from middle childhood into early adolescence (Lemaire & Lecacheur, 2011). While young children may draw upon their prior math skills to utilize strategies (e.g., finger counting or decomposition), they begin to narrow in on strategies that will be beneficial for them as well as suppress irrelevant strategies as they age. As such, children who use fewer strategies over time tend to perform better in math (Carr & Taasoobshirazi, 2017).

Interestingly, EFs did not relate to children's accuracy in third grade. This may be due in part to the strong performance at this time point ($M = 0.93$, range = 0.63 – 1.00) as the math task only included problems with sums of 20 or below. By third grade, children must be proficient in simple addition and subtraction problems or risk trailing behind their peers as they transition to learning more complex arithmetic operations (e.g., multiplication and division) that build on addition and subtraction. Moreover, our findings suggest that there are temporal variations in the importance of EFs for specific math skills. EFs likely play a central role in coordinating attentional resources during the initial acquisition of math subskills, whereas its role dissipates as concepts become fluent and automatic, cognitive load decreases, and children are able to rely on memory retrieval to implement those skills (LeFevre et al., 2013). The speed with which children respond may therefore be the most sensitive indicator of individual differences by this age.

The link between preschool EFs and RT in first grade reached a trend-level of significance ($p = .070$) and was positive, suggesting that preschool EFs may relate to slower RT in first grade. Given that we examined RT across accurate trials, this may suggest that children with stronger EF skills in preschool are better regulated to slow down to correctly identify the answer compared to children with lower EF skills. While EFs did not significantly contribute to second-grade RTs, the coefficient flipped to become negative, providing some evidence for a developmental shift towards quicker responses on accurate trials. By third grade, EFs uniquely and significantly contributed to children's faster RT. Thus, children with stronger EF skills in preschool quickly and accurately solved problems in third grade. The indirect effects of preschool EFs to third-grade RT via first- and second-grade RTs were not significant, likely due to the changing nature of this correlation over time. Given that most children are accurate in their responses by third grade, EFs support children to process and verbalize the correct response more rapidly.

4.3. Strengths, limitations, and future directions

Overall, this study employed longitudinal data to examine associations between preschool EFs, prior math abilities, and arithmetic problem-solving skills. An important aspect of this study included the direct assessments of children's arithmetic skills across multiple time points in elementary school. However, due to lapses in funding, children's kindergarten arithmetic skills were not assessed. It is likely, given our findings, that kindergarten accuracy and speed on arithmetic problems would have mediated links between preschool EFs and math skills and later arithmetic.

Furthermore, this study highlights how EFs and prior math abilities longitudinally relate to specific math skills, rather than examining children's general math achievement on standardized tests. By studying and uncovering how EFs, math abilities, and arithmetic problem-solving relate to one another, we can begin to understand the complex associations between domain-general and domain-specific skills. Recent research provides support that early math abilities depend on children's EFs (Bisagno et al., 2023), which is further evidenced by the bidirectional associations between early EFs and math skills (Miller-Cotto & Byrnes, 2020; Schmitt et al., 2017; Welsh et al., 2010). Given the dynamic interplay between EFs and early math abilities in the preschool years, it may be beneficial to examine the associations between EFs and specific math skills over time as children progress through elementary school.

It is worthwhile to draw attention to the task selection of preschool measures. For instance, EF tasks typically believed to assess working memory can capture updating or capacity (i.e., attending to chunks of information), although these terms are used synonymously, or perhaps not often specified from one another, in developmental literature. A recent study found that updating, a distinct yet interrelated construct, depends on capacity in preschool (Panesi et al., 2022). While the current study used three working memory tasks that are typically categorized as measures of updating, it is possible that one or more of the tasks assessed children's capacity. Overall, the types of measures used can drive the overall structure of EFs and researchers must continue to carefully determine and report on the characteristics of the tasks used for the construction of EF composite measures in future studies. Additionally, children's preschool math abilities were measured using the TEMA, which tests early numeracy and counting skills. While these abilities are highly predictive of later arithmetic skills (Malone et al., 2022), other early math skills such as geometry, patterning, and measurement skills are also fundamental for later math performance (Nguyen et al., 2016). By examining other domains of early math skills in preschool, we can begin to understand which sub-domains of math skills are important to support early on as well as where to intervene for children who may struggle academically in math.

Descriptive and *t*-test results indicated that children significantly improved in their accuracy across first to third grade on this task and performed extremely well in third grade ($M = 0.93$, range $= 0.63 – 1.00$). This high performance suggests possible ceiling effects, which could have generated biased estimates. However, this study also included children's RTs on the arithmetic problems, which demonstrated significant variability across all three grades. Additionally, children completed the same math problems task across multiple grades, leading to potential training effects. While it seems that ceiling effects were more likely to be prevalent in this sample, as the tests were taken a year apart with children having many math experiences in between, it is also possible that a combination of training and ceiling effects could have led to students' robust performance in third grade. Inclusion of larger addition and subtraction problems (e.g., sums above 20 and 3-digit numbers) as well as simple multiplication problems (e.g., 3×3) would be beneficial for examining children's arithmetic processing in middle childhood. Research provides evidence for how EFs concurrently and longitudinally support solving word problems in middle and upper elementary (Agostino et al., 2010; Viterbori et al., 2015), given that children must coordinate information and skills to work through multiple steps. However, more work accounting for prior math abilities is necessary to ensure that researchers do not overestimate the associations between EFs and word problem-solving skills.

5. Conclusion

This study helps untangle the complex associations between preschool EFs, early numeracy abilities, and children's accuracy and speed on arithmetic problems across early elementary school. Importantly, we examined two predictors – EFs and early math abilities – that are especially salient for children's long-term overall achievement in math. While children may capitalize on their prior math abilities to complete arithmetic problems early on, preschool EFs hold a unique predictive value for arithmetic fluency into third grade. Thus, these results provide novel information on the specific skills that early childhood educators can target for long-term success in arithmetic problems. Overall, this study underscores the importance of supporting early math abilities and particularly EF skills for children's long-term gains for arithmetic problems in early elementary school.

Declarations of interest

None.

Data Availability

The authors do not have permission to share individual-level data.

Appendix A. Confirmatory factor analysis of executive function tasks

Task	Standardized Factor Loading	Standard Error	*p*-value
Nine Boxes	.308	.068	< .001
Delayed Alternation	.294	.069	< .001
Nebraska Barnyard	.607	.056	< .001
Big-Little Stroop	.507	.060	< .001
Go/No-Go	.587	.057	< .001
Shape School – inhibit	.334	.068	< .001
Shape School – switch	.438	.063	< .001
Trails – Switching	.361	.068	< .001
Modified Snack Delay	.365	.066	< .001

Appendix B. Correlation matrix for preschool EF tasks

	1	2	3	4	5	6	7	8
1. Nine Boxes								
2. Delayed Alternation	.23***							
3. Nebraska Barnyard	.17**	.08						
4. Big-Little Stroop	.16*	.19**	.38***					
5. Go/No-Go	.18**	.16**	.36***	.31***				
6. Shape School - inhibit	-.05	.12*	.20***	.07	.28***			
7. Shape School - switch	.12*	.14*	.24***	.24***	.25***	.11		
8. Trails - switching	.11	.10	.18**	.14*	.19**	.18**	.21***	
9. Modified Snack Delay	.20**	.14*	.26***	.07	.16**	.19**	.18**	.17**

*$p < .05$, **$p < .01$, ***$p < .001$.

Appendix C. Structural equation models standardized path coefficients

	Switching accuracy		
Direct pathways	β	SE	*p*-value
1st grade			
Preschool EF composite	0.180	0.067	.007
Preschool math score	0.369	0.061	< .001
2nd grade			
Preschool EF composite	0.144	0.076	.058
Preschool math score	0.053	0.068	.437
First grade outcome	0.471	0.071	< .001
3rd grade			
Preschool EF composite	0.052	0.079	.506
Preschool Math score	0.011	0.093	.905
Second grade outcome	0.588	0.093	< .001
Covariance			
EF with math	0.486	0.045	< .001
EF with male child	-0.135	0.059	.021
EF with child racial/ethnic minority	-0.181	0.063	.004
EF with income	0.304	0.057	< .001
EF with maternal education	0.281	0.053	< .001
Math with male child	-0.011	0.061	.857
Math with child racial/ethnic minority	-0.099	0.063	.117
Math with income	0.242	0.055	< .001
Math with maternal education	0.269	0.055	< .001

References

Agostino, A., Johnson, J., & Pascual-Leone, J. (2010). Executive functions underlying multiplicative reasoning: Problem type matters. *Journal of Experimental Child Psychology, 105*(4), 286–305. https://doi.org/10.1016/j.jecp.2009.09.006

Ahmed, S. F., Kuhfeld, M., Watts, T. W., Davis-Kean, P. E., & Vandell, D. L. (2021). Preschool executive function and adult outcomes: A developmental cascade model. *Developmental Psychology, 57*(12), 2234–2249. https://doi.org/10.1037/dev0001270

Ashcraft, M. H. (1982). The development of mental arithmetic: A chronometric approach. *Developmental Review, 2*(3), 213–236. https://doi.org/10.1016/0273-2297(82)90012-0

Ashcraft, M. H. (1987). Children's knowledge of simple arithmetic: A developmental model and simulation. In J. Bisanz, C. J. Brainerd, & R. Kail (Eds.), *Formal methods in developmental psychology* (pp. 302–338). New York: Springer. https://doi.org/10.1007/978-1-4612-4694-7_9.

Aunola, K., Leskinen, E., Lerkkanen, M.-K., & Nurmi, J.-E. (2004). Developmental dynamics of math performance from preschool to grade 2. *Journal of Educational Psychology, 96*(4), 699–713. https://doi.org/10.1037/0022-0663.96.4.699

Bellon, E., Fias, W., & De Smedt, B. (2019). More than number sense: The additional role of executive functions and metacognition in arithmetic. *Journal of Experimental Child Psychology, 182*, 38–60. https://doi.org/10.1016/j.jecp.2019.01.012

Bentler, P. M. (1990). Comparative fit indexes in structural models. *Psychological Bulletin, 107*(2), 238–246. https://doi.org/10.1037/0033-2909.107.2.238

Bisagno, E., Cadamuro, A., & Morra, S. (2023). Multiple influences of working memory capacity on number comprehension: The interplay with metacognition and number-specific prerequisites. *Journal of Experimental Child Psychology, 226*, Article 105568. https://doi.org/10.1016/j.jecp.2022.105568

Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In *Testing structural equation models* (pp. 136–162). Sage.

Bull, R., & Lee, K. (2014). Executive functioning and mathematics achievement. *Child Development Perspectives, 8*(1), 36–41. https://doi.org/10.1111/cdep.12059

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology, 19*(3), 273–293. https://doi.org/10.1207/S15326942DN1903_3

Camerota, M., Willoughby, M. T., & Blair, C. B. (2020). Measurement models for studying child executive functioning: Questioning the status quo. *Developmental Psychology, 56*(12), 2236–2245. https://doi.org/10.1037/dev0001127

Carlson, S. M., White, R. E., & Davis-Unger, A. C. (2014). Evidence for a relation between executive function and pretense representation in preschool children. *Cognitive Development, 29*, 1–16. https://doi.org/10.1016/j.cogdev.2013.09.001

Carr, M., & Alexeev, N. (2011). Fluency, accuracy, and gender predict developmental trajectories of arithmetic strategies. *Journal of Educational Psychology, 103*(3), 617–631. https://doi.org/10.1037/a0023864

Carr, M., & Taasoobshirazi, G. (2017). Is strategy variability advantageous? It depends on grade and type of strategy. *Learning and Individual Differences, 54*, 102–108. https://doi.org/10.1016/j.lindif.2017.01.015

Casey, B. M., Pezaris, E., Fineman, B., Pollock, A., Demers, L., & Dearing, E. (2015). A longitudinal analysis of early spatial skills compared to arithmetic and verbal skills as predictors of fifth-grade girls' math reasoning. *Learning and Individual Differences, 40*, 90–100. https://doi.org/10.1016/j.lindif.2015.03.028

Clark, C. A. C., Pritchard, V. E., & Woodward, L. J. (2010). Preschool executive functioning abilities predict early mathematics achievement. *Developmental Psychology, 46*(5), 1176–1191. https://doi.org/10.1037/a0019672

Clements, D. H., Sarama, J., & Germeroth, C. (2016). Learning executive function and early mathematics: Directions of causal relations. *Early Childhood Research Quarterly, 36*, 79–90. https://doi.org/10.1016/j.ecresq.2015.12.009

Coolen, I., Merkley, R., Ansari, D., Dove, E., Dowker, A., Mills, A., Murphy, V., Von Spreckelsen, M., & Scerif, G. (2021). Domain-general and domain-specific influences on emerging numerical cognition: Contrasting uni-and bidirectional prediction models. *Cognition, 215*, Article 104816. https://doi.org/10.1016/j.cognition.2021.104816

Cragg, L., & Gilmore, C. (2014). Skills underlying mathematics: The role of executive function in the development of mathematics proficiency. *Trends in Neuroscience and Education, 3*(2), 63–68. https://doi.org/10.1016/j.tine.2013.12.001

Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64*(1), 135–168. https://doi.org/10.1146/annurev-psych-113011-143750

Diamond, A., Prevor, M. B., Callender, G., & Druin, D. P. (1997). Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. *Monographs of the Society for Research in Child Development, 62*(4). https://doi.org/10.2307/1166208

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Ellis, A., Ahmed, S. F., Zeytinoglu, S., Isbell, E., Calkins, S. D., Leerkes, E. M., Grammer, J. K., Gehring, W. J., Morrison, F. J., & Davis-Kean, P. E. (2021). Reciprocal associations between executive function and academic achievement: A conceptual replication of Schmitt et al. (2017). *Journal of Numerical Cognition, 7*(3), 453–472. https://doi.org/10.5964/jnc.7047

Enders, C. K. (2011). Analyzing longitudinal data with missing values. *Rehabilitation Psychology, 56*(4), 267–288. https://doi.org/10.1037/a0025579

Espy, K. A. (1997). The shape school: Assessing executive function in preschool children. *Developmental Neuropsychology, 13*(4), 495–499. https://doi.org/10.1080/87565649709540690

Espy, K. A. (2016). The changing nature of executive control in preschool. *Monographs of the Society for Research in Child Development, 81*(4), 1–179. https://doi.org/10.1111/mono.12206

Espy, K. A., & Cwik, M. F. (2004). The development of a trial making test in young children: The TRAILS-P. *The Clinical Neuropsychologist, 18*(3), 411–422. https://doi.org/10.1080/138540409052416

Espy, K. A., Kaufmann, P. M., McDiarmid, M. D., & Glisky, M. L. (1999). Executive functioning in preschool children: Performance on A-not-B and other delayed response format tasks. *Brain and Cognition, 41*(2), 178–199. https://doi.org/10.1006/brcg.1999.1117

Espy, K. A., McDiarmid, M. M., Cwik, M. F., Stalets, M. M., Hamby, A., & Senn, T. E. (2004). The contribution of executive functions to emergent mathematic skills in preschool children. *Developmental Neuropsychology, 26*(1), 465–486. https://doi.org/10.1207/s15326942dn2601_6

Farrington-Flint, L., Vanuxem-Cotterill, S., & Stiller, J. (2009). Patterns of problem-solving in children's literacy and arithmetic. *British Journal of Developmental Psychology, 27*(4), 815–834. https://doi.org/10.1348/026151008×383148

Fuhs, M. W., Nesbitt, K. T., Farran, D. C., & Dong, N. (2014). Longitudinal associations between executive functioning and academic skills across content areas. *Developmental Psychology, 50*(6), 1698–1709. https://doi.org/10.1037/a0036633

Geary, D. C. (2011). Cognitive predictors of achievement growth in mathematics: A 5-year longitudinal study. *Developmental Psychology, 47*(6), 1539–1552. https://doi.org/10.1037/a0025510

Geary, D. C., Hoard, M. K., & Bailey, D. H. (2012). Fact retrieval deficits in low achieving children and children with mathematical learning disability. *Journal of Learning Disabilities, 45*(4), 291–307. https://doi.org/10.1177/0022219410392046

Ginsburg, H.P., & Baroody, A.J. (2003). *Test of early mathematics achievement—3rd Edition*. Pro-Ed.

Hu, L., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling: A Multidisciplinary Journal, 6*(1), 1–55. https://doi.org/10.1080/10705519909540118

Hughes, C., Dunn, J., & White, A. (1998). Trick or treat?: Uneven understanding of mind and emotion and executive dysfunction in "hard-to-manage" preschoolers. *Journal of Child Psychology and Psychiatry, 39*(7), 981–994. https://doi.org/10.1111/1469-7610.00401

IBM Corp. Released. (2020). *IBM SPSS Statistics for Windows, Version 27.0.* Armonk, NY: IBM Corp.

James, T. D., Choi, H.-J., Wiebe, S. A., & Espy, K. A. (2016). The changing nature of executive control in preschool: II. The preschool problem solving study: Sample, data, and statistical methods. *Monographs of the Society for Research in Child Development, 81*(4), 30–46. https://doi.org/10.1111/mono.12269

Jordan, N. C., Kaplan, D., Nabors Olah, L., & Locuniak, M. N. (2006). Number sense growth in kindergarten: A longitudinal investigation of children at risk for mathematics difficulties. *Child Development, 77*(1), 153–175. https://doi.org/10.1111/j.1467-8624.2006.00862.x

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*(3), 850–867. https://doi.org/10.1037/a0014939

Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., & Garcia-Barrera, M. A. (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin, 144*(11), 1147–1185. https://doi.org/10.1037/bul0000160

Kochanska, G., Murray, K. T., & Harlan, E. T. (2000). Effortful control in early childhood: Continuity and change, antecedents, and implications for social development. *Developmental Psychology, 36*(2), 220–232. https://doi.org/10.1037/0012-1649.36.2.220

Lee, K., Ng, S. F., & Bull, R. (2018). Learning and solving algebra word problems: The roles of relational skills, arithmetic, and executive functioning. *Developmental Psychology, 54*(9), 1758–1772. https://doi.org/10.1037/dev0000561

LeFevre, J.-A., Berrigan, L., Vendetti, C., Kamawar, D., Bisanz, J., Skwarchuk, S.-L., & Smith-Chant, B. L. (2013). The role of executive attention in the acquisition of mathematical skills for children in Grades 2 through 4. *Journal of Experimental Child Psychology, 114*(2), 243–261. https://doi.org/10.1016/j.jecp.2012.10.005

Lemaire, P., & Lecacheur, M. (2011). Age-related changes in children's executive functions and strategy selection: A study in computational estimation. *Cognitive Development*. https://doi.org/10.1016/j.cogdev.2011.01.002. S0885201411000220.
Lembke, E., & Foegen, A. (2009). Identifying early numeracy indicators for kindergarten and first-grade students. *Learning Disabilities Research & Practice, 24*(1), 12–20. https://doi.org/10.1111/j.1540-5826.2008.01273.x
Lerner, M. D., & Lonigan, C. J. (2014). Executive function among preschool children: Unitary versus distinct abilities. *Journal of Psychopathology and Behavioral Assessment, 36*(4), 626–639. https://doi.org/10.1007/s10862-014-9424-3
Lurie, L. A., Hagen, M. P., McLaughlin, K. A., Sheridan, M. A., Meltzoff, A. N., & Rosen, M. L. (2021). Mechanisms linking socioeconomic status and academic achievement in early childhood: Cognitive stimulation and language. *Cognitive Development, 58*, Article 101045. https://doi.org/10.1016/j.cogdev.2021.101045
Major, C. S., Paul, J. M., & Reeve, R. A. (2017). TEMA and dot enumeration profiles predict mental addition problem solving speed longitudinally. *Frontiers in Psychology, 8*, 2263. https://doi.org/10.3389/fpsyg.2017.02263
Malone, S. A., Pritchard, V. E., & Hulme, C. (2022). Domain-specific skills, but not fine-motor or executive function, predict later arithmetic and reading in children. *Learning and Individual Differences, 95*, Article 102141. https://doi.org/10.1016/j.lindif.2022.102141
Michel, E., Molitor, S., & Schneider, W. (2020). Executive functions and fine motor skills in kindergarten as predictors of arithmetic skills in elementary school. *Developmental Neuropsychology, 45*(6), 367–379. https://doi.org/10.1080/87565641.2020.1821033
Mileva-Seitz, V. R., Ghassabian, A., Bakermans-Kranenburg, M. J., van den Brink, J. D., Linting, M., Jaddoe, V. W. V., Hofman, A., Verhulst, F. C., Tiemeier, H., & van IJzendoorn, M. H. (2015). Are boys more sensitive to sensitivity? Parenting and executive function in preschoolers. *Journal of Experimental Child Psychology, 130*, 193–208. https://doi.org/10.1016/j.jecp.2014.08.008
Miller, M. R., Giesbrecht, G. F., Müller, U., McInerney, R. J., & Kerns, K. A. (2012). A latent variable approach to determining the structure of executive function in preschool children. *Journal of Cognition and Development, 13*(3), 395–423. https://doi.org/10.1080/15248372.2011.585478
Miller-Cotto, D., & Byrnes, J. P. (2020). What's the best way to characterize the relationship between working memory and achievement?: An initial examination of competing theories. *Journal of Educational Psychology, 112*(5), 1074–1084. https://doi.org/10.1037/edu0000395
Moll, K., Snowling, M. J., Göbel, S. M., & Hulme, C. (2015). Early language and executive skills predict variations in number and arithmetic skills in children at family-risk of dyslexia and typically developing controls. *Learning and Instruction, 38*, 53–62. https://doi.org/10.1016/j.learninstruc.2015.03.004
Muthén, L.K., & Muthén, B.O. (2014). *Mplus (Version 7.3)*.
Nelson, T. D., Nelson, J. M., James, T. D., Clark, C. A. C., Kidwell, K. M., & Espy, K. A. (2017). Executive control goes to school: Implications of preschool executive performance for observed elementary classroom learning engagement. *Developmental Psychology, 53*(5), 836–844. https://doi.org/10.1037/dev0000296
Nesbitt, K. T., Baker-Ward, L., & Willoughby, M. T. (2013). Executive function mediates socio-economic and racial differences in early academic achievement. *Early Childhood Research Quarterly, 28*(4), 774–783. https://doi.org/10.1016/j.ecresq.2013.07.005
Nguyen, T., Watts, T. W., Duncan, G. J., Clements, D. H., Sarama, J. S., Wolfe, C., & Spitler, M. E. (2016). Which preschool mathematics competencies are most predictive of fifth grade achievement. *Early Childhood Research Quarterly, 36*, 550–560. https://doi.org/10.1016/j.ecresq.2016.02.003
Noldus, L. P., Trienes, R. J., Hendriksen, A. H., Jansen, H., & Jansen, R. G. (2000). The Observer Video-Pro: New software for the collection, management, and presentation of time-structured data from videotapes and digital media files. *Behavior Research Methods, Instruments, & Computers, 32*(1), 197–206.
Panesi, S., Bandettini, A., Traverso, L., & Morra, S. (2022). On the relation between the development of working memory updating and working memory capacity in preschoolers. *Journal of Intelligence, 10*(1), 5. https://doi.org/10.3390/jintelligence10010005
Pongsakdi, N., Kajamies, A., Veermans, K., Lertola, K., Vauras, M., & Lehtinen, E. (2020). What makes mathematical word problem solving challenging? Exploring the roles of word problem characteristics, text comprehension, and arithmetic skills. *ZDM, 52*(1), 33–44. https://doi.org/10.1007/s11858-019-01118-9
Purpura, D. J., Logan, J. A. R., Hassinger-Das, B., & Napoli, A. R. (2017). Why do early mathematics skills predict later reading? The role of mathematical language. *Developmental Psychology, 53*(9), 1633–1642. https://doi.org/10.1037/dev0000375
Purpura, D. J., & Lonigan, C. J. (2013). Informal numeracy skills: The structure and relations among numbering, relations, and arithmetic operations in preschool. *American Educational Research Journal, 50*(1), 178–209. https://doi.org/10.3102/0002831212465332
Raghubar, K. P., Barnes, M. A., & Hecht, S. A. (2010). Working memory and mathematics: A review of developmental, individual difference, and cognitive approaches. *Learning and Individual Differences, 20*(2), 110–122. https://doi.org/10.1016/j.lindif.2009.10.005
Raver, C. C., Blair, C., Willoughby, M., & Family Life Project Key Investigators. (2013). Poverty as a predictor of 4-year-olds' executive function: New perspectives on models of differential susceptibility. *Developmental Psychology, 49*(2), 292–304. https://doi.org/10.1037/a0028343
Rhemtulla, M., van Bork, R., & Borsboom, D. (2020). Worse than measurement error: Consequences of inappropriate latent variable measurement models. *Psychological Methods, 25*(1), 30–45. https://doi.org/10.1037/met0000220
Ribner, A. D., Willoughby, M. T., & Blair, C. B. (2017). Executive function buffers the association between early math and later academic skills. *Frontiers in Psychology, 8*, 869. https://doi.org/10.3389/fpsyg.2017.00869
Rittle-Johnson, B., Fyfe, E. R., Hofer, K. G., & Farran, D. C. (2017). Early math trajectories: Low-income children's mathematics knowledge from ages 4 to 11. *Child Development, 88*(5), 1727–1742. https://doi.org/10.1111/cdev.12662
Rohrer, D., Dedrick, R. F., & Hartwig, M. K. (2020). The scarcity of interleaved practice in mathematics textbooks. *Educational Psychology Review, 32*(3), 873–883. https://doi.org/10.1007/s10648-020-09516-2
Scalise, N. R., & Ramani, G. B. (2021). Symbolic magnitude understanding predicts preschoolers' later addition skills. *Journal of Cognition and Development, 22*(2), 185–202. https://doi.org/10.1080/15248372.2021.1888732
Schmitt, S. A., Geldhof, G. J., Purpura, D. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology, 109*(8), 1120–1140. https://doi.org/10.1037/edu0000193
Shrager, J., & Siegler, R. S. (1998). SCADS: A model of children's strategy choices and strategy discoveries. *Psychological Science, 9*(5), 405–410.
Shrout, P. E., & Bolger, N. (2002). Mediation in experimental and nonexperimental studies: New procedures and recommendations. *Psychological Methods, 7*(4), 422–445. https://doi.org/10.1037/1082-989X.7.4.422
Simanowski, S., & Krajewski, K. (2019). Specific preschool executive functions predict unique aspects of mathematics development: A 3–year longitudinal study. *Child Development, 90*(2), 544–561. https://doi.org/10.1111/cdev.12909
Simpson, A., & Riggs, K. J. (2006). Conditions under which children experience inhibitory difficulty with a "button-press" go/no-go task. *Journal of Experimental Child Psychology, 94*(1), 18–26. https://doi.org/10.1016/j.jecp.2005.10.003
Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly, 19*(1), 99–120. https://doi.org/10.1016/j.ecresq.2004.01.002
StataCorp. (2017). *Stata Statistical Software (Release 15) [Computer software]*. StataCorp LLC.
Vanbinst, K., Ghesquière, P., & De Smedt, B. (2012). Numerical magnitude representations and individual differences in children's arithmetic strategy use. *Mind, Brain, and Education, 6*(3), 129–136. https://doi.org/10.1111/j.1751-228X.2012.01148.x
Verdine, B. N., Irwin, C. M., Golinkoff, R. M., & Hirsh-Pasek, K. (2014). Contributions of executive function and spatial skills to preschool mathematics achievement. *Journal of Experimental Child Psychology, 126*, 37–51. https://doi.org/10.1016/j.jecp.2014.02.012
Viterbori, P., Usai, M. C., Traverso, L., & De Franchis, V. (2015). How preschool executive functioning predicts several aspects of math achievement in Grades 1 and 3: A longitudinal study. *Journal of Experimental Child Psychology, 140*, 38–55. https://doi.org/10.1016/j.jecp.2015.06.014
Watts, T. W., Duncan, G. J., Siegler, R. S., & Davis-Kean, P. E. (2014). What's past is prologue: Relations between early mathematics knowledge and high school achievement. *Educational Researcher, 43*(7), 352–360. https://doi.org/10.3102/0013189×14553660

Welsh, J. A., Nix, R. L., Blair, C., Bierman, K. L., & Nelson, K. E. (2010). The development of cognitive skills and gains in academic school readiness for children from low-income families. *Journal of Educational Psychology, 102*(1), 43–53. https://doi.org/10.1037/a0016738

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A. C., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology, 108*(3), 436–452. https://doi.org/10.1016/j.jecp.2010.08.008

Willoughby, M. T., Blair, C. B., Wirth, R. J., Greenberg, M., & The Family Life Project Investigators. (2012). The measurement of executive function at age 5: Psychometric properties and relationship to academic achievement. *Psychological Assessment, 24*(1), 226–239. https://doi.org/10.1037/a0025361