EVALUATING COGNITIVE AND ACADEMIC ACHIEVEMENT FACTORS AS PREDICTORS OF MATH ACHIEVEMENT IN KINDERGARTEN

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CHAPTER 1

Introduction

Early mathematics is essential to later math achievement and general academic achievement. Math instruction in early grades helps children develop problem-solving skills needed in their everyday lives (Master, n.d.). Research has shown that mathematical knowledge in preschool (pre-K; e.g., Watts et al., 2014) and at kindergarten entry and exit (Morgan et al., 2009; 2019) are strong predictors of later school outcomes across academic domains (Duncan et al., 2007). Watts et al. (2014) found that math performance in pre-K and first grade, as well as early growth in math skills, were significant predictors of math achievement at age 15. Given the importance of early mathematics for later math and general academic achievement, it is critical for both assessment and intervention purposes to know more about the factors that affect the development of early mathematical knowledge and skills. Therefore, the purpose of the current study was to investigate whether there are any factors at the end of pre-K that predict math achievement in kindergarten, over and above the mathematical knowledge acquired by these young children by the end of the pre-K year.

Meta-analyses have found that domain-general and domain-specific factors predict math achievement (De Smedt, 2022). Domain-general factors are variables that contribute broadly to learning in all domains including mathematics, such as language (Peng et al., 2020), executive function (EF; Spiegel et al., 2021), and visual spatial skills (Peng et al., 2019). Peng et al.'s (2018) meta-analysis found that students with math difficulties are also likely to experience deficits in domain-general cognitive processes (i.e., phonological processing, EF, attention, visual spatial processing) and that students with multiple academic difficulties are at-risk for more severe cognitive deficits (in phonological processing, EF, visuospatial skills). Domain-specific factors are variables that contribute to learning in a specific domain, in this case mathematics; for example, prior mathematical knowledge (Lin & Powell, 2022), approximate number sense (ANS; Schneider et al., 2017), and mathematical vocabulary (Lin et al., 2021) would also be considered to be domain-specific factors related to math achievement.

However, few meta-analyses have investigated the *relative* contributions of domain-general and domain-specific factors to mathematical development (De Smedt, 2022). A recent meta-analysis on the effects of academic and cognitive skills on subsequent math performance found that broad mathematics and working memory became more important with increasing age (Lin & Powell, 2022). This suggests that students' mathematical skills themselves (i.e., the accumulation of mathematical knowledge and fluency) become increasingly important across the grades for predicting achievement (Watts et al., 2014; Morgan et al., 2019).

Predictors of Mathematical Knowledge

Language and Literacy

Language is an essential component for learning including mathematical development (Peng et al., 2020). Research has found bidirectional relations between mathematics and general language (Peng et al., 2020), mathematics and mathematical language (comparative and spatial language) (Schmitt et al., 2019), and mathematics and reading (Lin & Powell, 2022). The comorbidity between reading and math disabilities is hypothesized to be related to overlapping domain-general cognitive processes, such as language, memory, and executive function (Barnes et al., 2020; Joyner & Wagner, 2020). For example, Peng et al. (2020) propose that the functions of language during mathematics are to retrieve mathematical knowledge from long-term memory and enhance working memory to employ language expression and comprehension skills during mathematical thinking and problem solving.

Research has shown that emerging literacy in pre-K (Watts et al., 2014) and kindergarten (Duncan et al., 2007) more strongly predict later math achievement than working memory or attention skills. Lin and Powell's (2022) meta-analysis found that word reading was consistently a robust predictor of later math performance even when considered alongside other literacy, math, and cognitive skills. In kindergarten, a bi-directional relation emerges between math and literacy skills during the first year of formal schooling (Schmitt et al., 2017). Morgan et al. (2019) found that high reading performance in kindergarten acted as a protective factor against belonging to the most at-risk group for mathematical difficulties in grades 1 to 3. Peng et al. (2018) found that comorbid math and reading difficulties were related to more severe cognitive deficits as did Barnes et al. (2020) for children at risk for comorbid difficulties in reading and math in pre-K. These findings highlight the importance of considering reading skills when predicting future math performance, and for considering developmental precursors of literacy skills such as phonological awareness and print knowledge (e.g., letters of the alphabet) when predicting math achievement in young children.

Approximate Number System Accuity

Approximate Number System (ANS) is the ability to estimate numerical magnitudes and is commonly measured using a non-symbolic number comparison task (i.e., dots). Meta-analyses have found significant, but small effect sizes for the relation between non-symbolic ANS and math achievement (Fazio et al., 2014; Schneider et al., 2017). In preschoolers, performance accuracy is higher on congruent ANS trials, where surface area and numeracy of dots are proportional, compared to incongruent ANS trials, where surface area and numeracy of dots are inversely proportional (Rodriguez & Ferreira, 2023). Research has shown that only performance on incongruent ANS trials differentiates those with developmental dyscalculia from typically developing peers and is also related to math achievement more generally (i.e., the congruency effect; Miller et al., 2022b; Wilkey et al., 2020).

Wilkey et al. (2020) interpreted performance on incongruent ANS trials as a measure of EF in a numerical context beyond what is accounted for by general EF, and it has been suggested by others to tap visual spatial working memory or VSWM (Bugden & Ansari, 2013), and inhibitory control (Fuhs & McNeil, 2013; Rodriguez & Ferreira, 2023). Moreover, Coolen et al. (2021) found in preschool-age children that the magnitude comparison task loaded onto a latent factor distinct from the latent factors for EF (a domain-general factor) and early numeracy (domain-specific factor). This suggests that ANS emerges as a unique domain-specific factor predicting later math achievement as early as 3 years old. Based on these findings, I hypothesize that ANS acuity for incongruent trials at the end of pre-K would uniquely contribute to math achievement in kindergarten.

Executive Functioning

Executive functioning (EF) refers to a set of cognitive processes that aid goal-directed and adaptive behaviors (Garon et al., 2008). Research has found weak to moderate positive correlations between mathematics and EF and its core components, including working memory (the system that maintains and manipulates information; Peng et al., 2016), inhibitory control (the mechanism that blocks or suppresses irrelevant information or responses; Lee & Lee, 2022), and cognitive flexibility (the ability to switch tasks; Santana et al., 2022), across grades K to 6 (Spiegel et al., 2021). Among these components, working memory is the most commonly reported domain-general predictor of subsequent math achievement (Nogues & Dorneles, 2021) and often exhibits the largest correlations with math skills (Spiegel et al., 2021). Kahl et al. (2022) reported a bidirectional relationship between working memory and math achievement in middle childhood and found that students with strong working memory at ages 6 to 7 were the most likely to experience the greatest gains in math achievement three years later.

Because EF is robustly related to math, it is not surprising that EF deficits, especially in working memory, are associated with math difficulties (Peng et al., 2018). Morgan et al. (2019) reported that low working memory, inhibition, and cognitive flexibility (<10th percentile) in kindergarten increased the odds of belonging to the at-risk academic achievement groups (-2SD) in grades 1 to 3 by 5.0, 2.2, and 1.8 times respectively. However, low EF did not predict group membership for students in the highest mathematic achievement group, suggesting that students with high achievement are less likely to be impacted by low EF skills since they can rely on their long-term knowledge of mathematics. Ribner et al. (2017) reported similar findings in preschoolers. They found that high EF (working memory, inhibition, and cognitive flexibility) in pre-K was a protective factor for 5th grade math achievement in children with low mathematical knowledge in pre-K. However, for children with high mathematical knowledge in pre-K, low EF was no longer a risk-factor. Students in the low average and at-risk achievement groups, who have less academic knowledge, may be more likely to rely on their EF skills during mathematic tasks (Morgan et al., 2019), which themselves may be low (Peng et al., 2018). Prior academic achievement may mediate the relationship between EF and math achievement by reducing the cognitive resources required to process familiar knowledge (Lin & Powell, 2022). This is consistent with the domain-specific model of working memory, in which mathematical knowledge stored in long-term memory can facilitate or supplant working memory (Peng & Swanson, 2022).

EF in preschool is often investigated as a unitary construct with dissociable components using confirmatory factor analysis (e.g., Coolen et al., 2021; Schmitt et al., 2017) and composite scores (e.g., Schmitt et al., 2019). Research suggests that EF and its relations to academic tasks are dynamic in preschool. Coolen et al. (2021) found that their latent EF factor (inhibition, working memory, and selective attention) predicted growth in their latent early numeracy factor 5 months later in children ages 3 to 4. Schmitt et al. (2017) found a bi-directional relation between their latent EF factor (general EF, working memory, inhibition, and cognitive switching) and math performance in pre-K, which then became unidirectional in kindergarten. Fall kindergarten EF and math equally predicted spring kindergarten math. These findings suggest that EF and math development may support each other's early development.

Watts et al. (2014) used multiple regression analysis to directly compare measures of EF factors (working memory, inhibition, and sustained attention), reading, math, vocabulary, and auditory processing. They found that math performance in pre-K and first grade, as well as early growth in math skills, were the strongest predictors of math achievement in elementary and high school, followed by reading performance, working memory, and auditory processing.

In sum, the literature on EF and mathematics suggests that EF is an important predictor of math achievement in the transition to kindergarten, but also that prior math knowledge and other skills such as language may also uniquely predict math achievement in kindergarten. Based on these findings, particularly those that consider the protection that either strong EF or stronger math knowledge can afford for later development of mathematics skills, I hypothesize that both math achievement and EF will uniquely contribute to math achievement in kindergarten.

Attention

Attention is considered a precursor skill to EF and a fundamental component of all EF tasks (Garon et al., 2008). The rapid growth of EF observed between ages 3 and 5 is attributable to the maturation and integration of attention systems, which support sustained attention, selective attention, and conflict resolution during EF tasks (Garon et al., 2008). Research has shown that attention, as measured by teacher ratings (Duncan et al., 2007), mother ratings (McClelland et al., 2013), and direct measures (Isbell et al., 2018), predicted later math achievement; however, see Steele et al. (2012) and Watts et al. (2014). Math disabilities are associated with attention difficulties, even without an ADHD diagnosis (Tannock, 2013). A metanalysis conducted by Peng et al. (2018) found that the relation between attention deficits and mathematics was stronger among younger students with mathematics difficulties than older students with mathematical difficulties, which is consistent with attention's role as a foundational skill that contributes to more complex executive processes.

Steele et al. (2012) found that in 3- to 6-year-olds sustained attention was correlated with numeracy performance a year later while executive attention (i.e., inhibition) was associated with current numeracy performance. Barnes et al. (2020) found that sustained attention at the beginning of pre-K differentiated three groups at the end of pre-K: not-at-risk, risk for math difficulties, and risk for math and reading difficulties. Executive attention differentiated between two groups: not-at-risk and those with risk for any math difficulties. Steele et al. (2012) found that in preschool-aged children direct measures of attention, but not teacher ratings of attention were related to academic performance. Teacher-rated assessments may not capture internal behaviors of attention. Considering this research on attention and math in young children, this study used direct child measures of attention at the end of pre-K to predict kindergarten math.

Visual Spatial Skills

Visual spatial skills support the ability to mentally manipulate information about objects in space and environment (Verdine et al., 2017). Longitudinal studies have found that spatial skills in kindergarten predicted later math achievement in first grade children in Hong Kong (Fung et al., 2020) and in second grade children in Switzerland (Frick, 2019), after controlling for initial math performance (reviewed in Cui & Guo, 2017). Peng et al. (2019) found bidirectional relations between matrix reasoning (i.e., non-verbal reasoning) and mathematics during middle childhood, and this relation was stronger for more complex mathematic skills.

The relationship between spatial skills and mathematics in pre-K is less clear. Rittle-Johnson et al. (2019) found in pre-K that although spatial skills were associated with math performance, they did not significantly predict math outcomes seven months later after accounting for initial math performance. This suggests that the math-related aspects of spatial skills were captured by prior math knowledge. In contrast, Verdine et al. (2017) found that spatial skills at age 3 predicted math performance at age 4; however, they did not find a predictive effect for initial math skills. More longitudinal research is needed on the relationship between spatial skills and mathematics during the transition from pre-K to kindergarten. In the current study, visual-spatial skills at the end of pre-K were tested along with the other potential predictors reviewed above in relation to kindergarten math achievement.

Purpose of the Current Study

As reviewed above, research has investigated the relationship between several domain-general and domain-specific factors with individual differences in mathematical achievement; however, most studies consider the relations of only a few of these predictors to math in any one study. Much less is known about how the multiple factors reviewed above contribute to math performance when considered together within the same student population and for children who are in the transition to kindergarten. This study is a secondary data analysis of a randomized controlled trial (Barnes et al., 2016) with children who entered pre-K with low math knowledge.

The purpose of this study is to investigate which language/literacy and cognitive factors at the end of pre-K predict math achievement in kindergarten, over and above the mathematical knowledge acquired by these young children by the end of pre-K year. Based on the findings discussed above for how early math knowledge, ANS acuity, various EFs, early literacy, and visual-spatial skills are related to later math achievement at kindergarten, my hypotheses were as follows: (1) Math performance at the end of pre-K will be the strongest predictor of later math achievement in kindergarten; (2) After math performance, early literacy at the end of pre-K will be the next strongest predictor of kindergarten math achievement; (3) Incongruent ANS acuity will predict math achievement over and above previous math achievement and language/early literacy; and (4) EFs will predict additional unique variance in kindergarten math achievement, with working memory being the largest EF predictor of math achievement. I did not make a prediction for visual-spatial skills based on the inconsistent findings in the literature.

CHAPTER 2

Methods

In this study I conducted a secondary data analysis of a randomized controlled trial originally conducted by Barnes et al. (2016). The parent study tested the effects of a math intervention (Pre-K Mathematics Tutorial; PKMT) and attention-training intervention on math achievement in pre-K students with low math knowledge. The study was conducted in Houston, Texas, and the San Francisco Bay Area, California. However, for this study, I used only the Texas sample because of significant differences in the quality of Tier 1 math instruction between states (with quality higher in Texas) and also because one state (Texas) used a bilingual math program at Tier 1 whereas the other state (California) taught math in English regardless of child home language. Further, only the Texas sample was assessed for phonological awareness at the end of pre-K, which was one of the major predictors for this study.

Participants

In the parent study, students were recruited for participation based on their math skills at the beginning of pre-K. Participants were eligible for the study if they scored four or lower on an abbreviated Child Math Assessment (CMA), which correlated to a score below the 25th percentile on the Test of Early Mathematics Ability, 3rd Edition (TEMA-3).

The Texas cohort included 277 preschool students. At pretest, they were, on average, 4.57 years old, and 45.5% were female. Students were primarily Hispanic (54.2%) and African

American (31.8%), with smaller percentages of students with mixed ethnicity (4.7%), White (3.2%), Asian American (0.7%), and unknown (5.4%) backgrounds. Thirteen of the 49 Texas classrooms provided most of their instruction, including for math, in Spanish. All students were from low-income families and were eligible to attend state pre-K programs.

Measures

Measures of math achievement, early literacy, domain-specific cognitive skills (i.e., incongruent ANS acuity), and domain-general cognitive skills (EFs, attention, visual-spatial skills) were used as predictors of later mathematic achievement in this study. All measures of predictors were administered at the end of pre-K. The outcome measure was the TEMA-3 scaled score measured at kindergarten. End of pre-K data were collected in May and kindergarten data were collected in February across two cohorts in 2012-2013 and 2013-2014. Both Spanish and English versions of the letter-word identification and phonological awareness measures were used. Additionally, a Spanish translation of the TEMA was used with permission from the test authors and all other measures including cognitive measures were delivered in the child's preferred language. Test language was selected based on students' primary and preferred languages. There were no effects of language due to these translations into Spanish (Barnes et al., 2020).

Test of Early Mathematics Ability, 3rd Edition (TEMA-3)

The TEMA-3 (Ginsburg & Baroody, 2003) measures the informal and formal mathematical knowledge of children between ages of 3-0 and 8-11 years. It is an individually administered test approximately 40 minutes in duration. It contains 72 items across the several mathematical domains including, numbering skills, number-comparison facility, mastery of number facts, and calculation skills. Test-retest reliability ranges from 0.82 to 0.93; within-sample test-retest reliability was 0.85. The TEMA-3 is a commonly used measure of math achievement in the pre-K and kindergarten years.

Letter-Word Identification

The Letter-Word Identification subtest from the Woodcock-Johnson Tests of Academic Achievement-3rd Edition NU (WJ-3 NU; Woodcock, McGrew, & Marther, 2007) and Identificación de letras y palabras from the Batería III Woodcock-Muñoz (Muñoz-Sandoval, Woodcock, McGrew, & Mather, 2005) measures letter recognition and word reading. Internal consistency for this age was high (α = 0.98); within-sample internal consistency was 0.87.

Phonological Awareness

The Phonological Awareness subtest of the Test of Preschool Early Literacy or TOPEL (Lonigan, Wagner, Torgesen, & Rashotte, 2007) and the Spanish Preschool Early Literacy Assessment or SPELA (Lonigan, 2012) measure word elision and blending abilities across 27 items. Internal consistency was above α = .89 (Goodrich & Lonigan, 2017). Raw scores were converted into z-scores because published norms were available for only the TOPEL; the author of the SPELA allowed the research team to use the version of the SPELA that was undergoing norming.

Incongruent Approximate Number System (ANS) Acuity

Panamath (Panamath.org, 2010-2011) measures approximate number sense. Four practice trials are administered with feedback followed by 40 test trials. Students were asked to choose whether Elmo or Cookie Monster had more dots on their side. On incongruent trials, the surface area of dots was inversely proportional to the number of dots (i.e., the side with fewer dots had larger dots). Accuracy on only incongruent trials differentiates individuals with developmental dyscalculia from typically developing peers (i.e., congruency effect) and accounts for a wide range of math abilities (Wilkey et al., 2020), which is why only incongruent trials (n=20) were used as predictors. Total accuracy on incongruent trials was recorded. Within-sample test-retest reliability was 0.92.

Sustained Attention

The Child-Attention Networks Test (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005) measures sustained attention. The version used is similar to the one found in the National Institutes of Health Toolbox for the Assessment of Neurobiological and Behavioral Function – Cognition Battery (Bauer & Zelazo, 2014). It is a child-friendly version of the flanker task. The student must press the key on the keyboard that matches the direction in which the middle fish is swimming. On congruent trials the middle fish is facing the same direction as its neighbors. Total accuracy on congruent trials was recorded (Barnes et al., 2020). Within-sample test-retest reliability was 0.82.

Inhibition

The Child-Attention Networks Test (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005) measures inhibition (i.e., executive attention) using incongruent trials. On incongruent trials, the middle fish is facing the opposite direction as its neighbors and the child must ignore the neighboring fish and press the key on the keyboard that matches the direction in which the middle fish is swimming. Total accuracy on incongruent trials was recorded. Within-sample test-retest reliability was 0.82.

Working Memory

A child-friendly version of the Corsi-Blocks task with a span of 1 to 7 was used to measure visual-spatial working memory (VSWM; Bisanz, Sherman, Rasmussen, & Ho, 2005). The child must replicate the frog's jumping path across lily pads, which slowly increase in the number of jumps. Different types of working memory tasks (e.g., verbal, numerical, visual-spatial) all have comparable relations with mathematics (Peng et al., 2015); therefore, I refer to the measure of VSWM in this study simply as working memory. Total accuracy was recorded. Internal consistency for ages 4 to 5 was 0.70; Within-sample test-retest reliability was 0.70.

Matrix Reasoning

The Matrices subtest from the Kaufman Brief Intelligence Test, Second Edition (Kaufman & Kaufman, 2004) measures visual-spatial problem solving. Participants choose a picture on the bottom that most relates to the pattern shown in the pictures above, which may be concrete and abstract stimuli. The internal consistency reliability for ages 4 to 18 is 0.86.

Analysis Plan

This study was a secondary data analysis using multilinear regression models. Data were analyzed in IBM SPSS Statistics (Version 28). First, I looked at bivariate correlations between predictors measured at end of pre-K with the outcome (TEMA-3 scaled score at kindergarten). Predictors included age at kindergarten, TEMA-3 scaled score, phonological awareness Z-score, Letter-Word Identification scaled score, incongruent ANS acuity accuracy, inhibition (incongruent trial accuracy), sustained attention (congruent trial accuracy), visual spatial working memory, and KBIT Nonverbal scaled score.

The data were analyzed using four models using linear regressions. Models were constructed based on my four hypotheses. Model 1 included only two predictors of the TEMA-3 scaled score at kindergarten: age at kindergarten and TEMA-3 scaled score at end of pre-K (Hypothesis 1). Letter-Word Identification and phonological awareness scores were then added to Model 1 to test Hypothesis 2 (Model 2). Model 3 included all predictors from Model 2 and added incongruent ANS acuity trial accuracy (Hypothesis 3). Finally, Model 4 included all predictors from Model 3 and added inhibition, sustained attention, visual spatial working memory, and KBIT Nonverbal scaled score (Hypothesis 4). Each subsequent model tested for uniquely-significant predictors over and above previous models.

CHAPTER 3

Results

Bivariate correlations between the predictors and outcome (TEMA-3 scaled score at kindergarten) showed significant correlations between the outcome and the following predictors: age at kindergarten (r(262) = -.352, p<0.001), TEMA-3 scaled score at end of pre-K (r(254) =.723, p<0.001), phonological awareness Z-score (r(252) = .251, p<0.001), Letter-Word Identification scaled score (r(252) = .540, p<0.001), inhibition (Flanker incongruent trial accuracy, r(253) = -.281, p<0.001), visual spatial working memory (r(254) = .163, p<0.001), and KBIT Nonverbal scaled score (r(262) = .230, p<0.001) (see Table 1). As expected, the largest correlation was between TEMA-3 scaled scores at kindergarten and end of pre-K. ANS incongruent trials and sustained attention were not significantly correlated with TEMA-3 scaled scores at kindergarten. All other predictors were significantly correlated with TEMA-3 scaled scores at end of Pre-K. There was no evidence of multicollinearity between the predictors.

The regression for Model 1 (included predictors are age at kindergarten and TEMA-3 scaled score at end of pre-K) indicated an overall significant model (F(2,253) = 158.332, p<0.001) that explained 55.6% of the variance in TEMA-3 scaled scores at kindergarten (R^2 = 0.556) (see Table 2). Both age (b = -.190, t(255) = -4.354, p<0.001) and TEMA-3 scaled scores at the end of pre-K (b = .671, t(255) = 15.393, p<0.001) were uniquely-significant predictors.

Table 1

Correlations of Predictors with TEMA-3 Scaled Score at Kindergarten

Predictor	Pearson's Coefficient (*r*)
Age at kindergarten	-.352**
TEMA-3 scaled score at end of pre-K	.723**
Letter-Word identification	.540**
Phonological awareness	.251**
Incongruent ANS acuity	.103
Sustained attention	.096
Inhibition	.281**
Working memory	.163**
Matrix reasoning	.230**

Note. TEMA-3 = Test of Early Mathematics Ability, 3rd edition. ANS = approximate number system.
**$p < .01$

Table 2

Multiple Regression Models Predicting TEMA-3 Scaled Score at Kindergarten

Variable	β	R^2
Model 1		0.552
Age at kindergarten	-.190**	
TEMA-3 scaled score at end of pre-K	.671**	
Model 2		0.578
Age at kindergarten	-.173**	
TEMA-3 scaled score at end of pre-K	.575**	
Letter-Word identification	.156**	
Phonological awareness	.054	
Model 3		0.579
Age at kindergarten	-.167**	
TEMA-3 scaled score at end of pre-K	.584**	
Letter-Word identification	.156**	
Phonological awareness	.058	
Incongruent ANS acuity	-.038	
Model 4		0.598
Age at kindergarten	-.182**	
TEMA-3 scaled score at end of pre-K	.549**	
Letter-Word identification	.163**	
Phonological awareness	.023	
Incongruent ANS acuity	-.034	
Sustained attention	-.074	
Inhibition	.142**	
Working memory	.010	
Matrix reasoning	.033	

Note. TEMA-3 = Test of Early Mathematics Ability, 3rd edition. ANS = approximate number system.
**$p < .01$

The regression for Model 2 (included predictors are Model 1 predictors, phonological awareness Z-score, and Letter-Word Identification scaled score) indicated an overall significant model ($F(4,252) = 84.912$, $p<0.001$) that explained 57.8% of the variance in TEMA-3 scaled score at kindergarten ($R^2 = 0.578$). Age ($b = -.173$, $t(252) = -3.814$, $p<0.001$), TEMA-3 scaled score at end of pre-K ($b = .575$, $t(252) = 11.296$, $p<0.001$) and Letter-Word Identification scaled score ($b = .156$, $t(252) = 3.012$, $p=0.003$) were uniquely-significant predictors (Table 2).

The regression for Model 3 (included predictors are Model 2 predictors and incongruent ANS acuity (Panamath incongruent trials)) indicated an overall significant model ($F(5,252) = 68.020$, $p<0.001$) that explained 57.9% of the variance in TEMA-3 scaled score at kindergarten ($R^2 = 0.579$). Age ($b = -.167$, $t(252) = -3.642$, $p<0.001$), TEMA-3 scaled score at end of pre-K ($b = .584$, $t(252) = 11.251$, $p<0.001$) and Letter-Word Identification scaled score ($b = .156$, $t(252) = 3.019$, $p=0.003$) were uniquely-significant predictors (Table 2).

The regression for Model 4 (included predictors are Model 3 predictors, sustained attention (Flanker congruent trial accuracy), inhibition (Flanker incongruent trial accuracy), visual-spatial working memory accuracy, and KBIT Nonverbal scaled scores) indicated an overall significant model ($F(9,251) = 39.962$, $p<0.001$) that explained 59.8% of the variance in TEMA-3 scaled score at kindergarten ($R^2 = 0.598$). Age ($b = -.182$, $t(251) = -3.810$, $p<0.001$), TEMA-3 scaled score at end of pre-K ($b = .549$, $t(251) = 9.998$, $p<0.001$), Letter-Word Identification scaled score ($b = .163$, $t(251) = 3.174$, $p=0.002$), and inhibition ($b = .142$, $t(251) = 2.984$, $p=0.003$) were uniquely-significant predictors (Table 2).

CHAPTER 4

Discussion

The goal of this study was to investigate the relative contribution of domain-general factors (language/literacy, EFs, attention, visual-spatial skills) and domain-specific factors (previously acquire mathematical knowledge, ANS acuity) at the end of pre-K to math achievement in kindergarten. Research has established weak to moderate relations between math and language/literacy and cognitive factors. However, these factors tend to be studied independently from one another. This study found that when these end of pre-K factors were combined into one model, only early print knowledge (i.e., letter and simple word identification) and inhibition predicted math achievement in kindergarten, over and above end of pre-K math performance. Although most end of pre-K factors were significantly correlated with kindergarten math achievement, only these two were uniquely predictive with all other variables in the model.

Mathematical knowledge is critical to the development of mathematics. Research has found that mathematical knowledge in preschool (Watts et al., 2014) and at kindergarten entry and exit (Morgan et al., 2009; 2019) are strong predictors of later math achievement (Duncan et al., 2007). The importance of domain-specific knowledge to later mathematics increases with age (Lin & Powell, 2022). Based on these findings, I hypothesized that math performance at the end of pre-K would be the strongest predictor of later math achievement. Indeed, this study found that TEMA-3 at the end of pre-K was the largest predictor of TEMA-3 in kindergarten. Math performance at end of pre-K and age at kindergarten accounted for 55.2% of variance in math performance in kindergarten, suggesting that math knowledge accumulated by the end of pre-K in children who entered pre-K with very low levels of knowledge was critical and predictive of their mathematical performance in kindergarten. These findings indicate that math performance at end of pre-K may be used to identify students in kindergarten at-risk for math difficulties and underscore the importance of providing high-quality math instruction in pre-K to ensure that children enter kindergarten with foundational math knowledge (Barnes et al., 2016).

Effect of Literacy on Math Achievement

Research has found that word reading robustly predicts later math performance (Lin & Powell, 2022) when considered alongside other academic and cognitive factors, including phonological awareness (Duncan et al., 2007; Watts et al., 2014). Similarly, this study found that early print knowledge (e.g., letter and simple word recognition) was the strongest predictor of kindergarten math achievement after initial math performance. Additionally, early print knowledge was strongly correlated with end of pre-K math performance. Phonological awareness was not a significant predictor when included in the same model as letter-word identification, suggesting that letter-word identification at the end of pre-K taps something unique above and beyond phonological awareness in terms of early literacy and its relation to mathematics.

The relationship between math and reading has also been characterized by some researchers as a generalized school outcome related to domain-general processes (Unal et al., 2023; Vivian & Strasser, 2017). Meta-analyses report moderate to strong correlations between math and reading in elementary and middle school (Unal et al., 2023) and across the lifetime (Vivian & Strasser, 2017). Schmitt et al. (2017) found that a bidirectional relationship between math and literacy emerged in kindergarten, which the authors attributed to more standardized academic instruction in math and reading. Lin and Powell (2022) also interpreted reading and math measures as proxies for academic familiarity and experience in light of the dual-process theory of higher cognition. My study's findings support the body of research suggesting that math and literacy are interconnected school outcomes and reflect the importance of providing early and comprehensive instruction in both domains.

Effect of Domain-Specific Factor on Math Achievement

Research has shown that performance on ANS incongruent trials differentiate those with developmental dyscalculia from typically developing peers and is also related to math achievement more generally (Miller et al., 2022b; Wilkey et al., 2020). Incongruent ANS acuity is hypothesized to tap VSWM (Budgen & Ansari, 2013), inhibition (Fuhs & McNeil, 2013; Rodriguez & Ferreira, 2023), and EF in a numerical context (Wilkey et al., 2020). I hypothesized that ANS acuity on incongruent trials would predict math achievement over and above previous math achievement and language/early literacy. Although incongruent ANS acuity was weakly correlated with concurrent math achievement, inhibition, VSWM, and sustained attention (see Appendix A), which is consistent with the research discussed above, incongruent ANS acuity was not a significant correlate of later math achievement, nor did it account for unique variance in the regression models, suggesting that any math-related aspects of incongruent ANS acuity were captured by the end of pre-K math achievement measure.

Effect of Domain-General Factors on Math Achievement

Research has found weak to moderate positive correlations between mathematics and EF and its core components (working memory, inhibition, cognitive flexibility). Working memory is the most commonly reported domain-general predictor of subsequent math achievement (Nogues

& Dorneles, 2021) and often exhibits the largest correlations with math skills (Spiegel et al., 2021). I hypothesized that EFs would predict additional unique variance in kindergarten math achievement, with working memory being the largest EF predictor of math achievement. I found that while the combination of EF and visual-spatial measures accounted for additional variance in kindergarten math achievement over and above prior math knowledge, early literacy, and ANS acuity, working memory was not a significant unique predictor of math achievement. The only EF skill that uniquely predicted math achievement in kindergarten was inhibition, despite inhibition, working memory, and visual-spatial skills being significantly correlated with math achievement in kindergarten. Miller et al., (2022b) analyzed the same parent data set as this study and found that inhibition was the only EF skill at the end of pre-K that predicted concurrent math performance across math abilities in the entire sample (4^{th}-63^{rd} norm-referenced percentiles; see Epsy et al., 2004 for similar results).

The domain-specific model of working memory may explain why working memory was not a significant predictor of kindergarten math achievement in children who entered pre-K with low mathematical knowledge ($<25^{th}$ percentile TEMA-3). According to this model, mathematical knowledge stored in long-term memory can support or enhance working memory when performing mathematical tasks (Peng & Swanson, 2022). However, children in this study may not have acquired enough long-term memories of mathematics by the end of pre-K to draw upon their working memory when performing mathematical tasks in kindergarten. Further, for children with limited math knowledge (e.g., can rote count to 3), they may primarily deploy EF skill to inhibit distractors and prevent prepotent responding to those distractors. For example, young children may need to inhibit peripheral distractors (e.g., external visual or auditory distraction), deal with cognitive distractors (e.g., when spatial or other visual characteristics of stimuli compete with quantitative characteristics such as when a small number of objects takes up more space than a larger number of objects or when objects to count are also attractive toys), and over-ride misconceptions as they develop foundational math knowledge (identifying numbers 1 to 10) and engage in mathematical tasks (counting to 10 using one-to-one correspondence) (Lee & Lee, 2019).

As reviewed by Ashkenazi and Blum-Cahana (2023), inhibition is important for mathematical computation because during math fact retrieval (e.g., 3+4=7), multiple solutions are activated (4, 5, and 7) which need to be suppressed (4 and 5). Research with 9- and 10-year-old children has found that hypersensitivity-to-interference is associated with low addition and multiplication fact fluency (Visscher & Noel, 2014), and deficits in VSWM and inhibition have been linked to developmental dyscalculia (Szucs et al., 2013). Theoretically, inhibition could play a similarly role in number naming and counting in pre-K. For example, when identifying the digit 4, the words “four” and “five” may both be activated or when counting objects, the number just counted may compete with the next number in the sequence (“. . . three, four, four, five, six . . .”). Further research is needed to identify potential mechanisms linking inhibition and mathematics (Barnes & Peng, in press). Nonetheless, this study’s finding that inhibition is uniquely predictive of later math achievement highlights a potential important role of inhibition in math performance for low-performing students in kindergarten.

Future research is needed to investigate how previously acquired math knowledge impacts the relations between literacy, language, cognitive factors, and math achievement across the full range of math ability levels. Components of EFs should be individually considered as early as pre-K because research has shown that children with different math ability levels are likely to draw upon different aspects of their EF (Miller et al., 2022b; Morgan et al., 2019; Ribner et al., 2017).

Limitations

Emergent literacy skills can be categorized as code skills and oral language skills (NICHD Early Child Care Research Network, 2005). Phonological awareness and print knowledge were used as measures of early literacy skills (i.e., code skills). For a richer understanding of how language predicts math achievement, future studies should also include measures of oral language skills. LeFevre and colleagues have represented the linguistic pathway with measures of receptive vocabulary and phonemic awareness (LeFevre et al., 2010; Sowinski et al., 2015) and, most recently, just with measures of receptive vocabulary (Di Lonardo Burr et al., 2022). Indeed, Peng et al. (2020) found stronger associations between math achievement and oral comprehension/vocabulary than math achievement and phonemic awareness.

Language is believed to play a role in math development by facilitating memory recall of mathematical knowledge and enhancing EFs during mathematical thinking (Peng et al., 2020); engaging in higher orders of reasoning and reflection (Zelazo, 2015); and using more complex language to understand math concepts (Schmitt et al., 2019). Schmitt et al. (2019) found that a bidirectional association between mathematical language and EF development emerged in pre-K, suggesting that complex language is important to mathematical knowledge and EF (Purpura et al., 2017). The relationship between language and math achievement for children who enter pre-K with low levels of math knowledge remains unknown. Prior mathematical knowledge may mediate the role of language as it relates to EF.

Preschool EF is often analyzed as a unitary construct rather than individual components of EF. In this study, I directly consider working memory, sustained attention, and inhibition. Future research should consider the role of cognitive flexibility in math development, which is important to procedural math, patterning, and place value (Santana et al., 2022). Recent meta-analyses have reported weak to moderate relations between cognitive flexibility and math achievement in preschoolers (Santana et al., 2022) and elementary-aged children (Speigel, et al., 2021).

Due to the limited scope of this paper, I did not perform a moderation analysis to investigate whether the strength of the relationship between pre-K predictors and kindergarten math achievement varied across the wide range of kindergarten math ability levels present in this sample. Research has found that strong math knowledge has shown to be a protective factor against low-EF, suggesting differences in the relationship between EF and math achievement across math ability levels (Morgan et al., 2019; Ribner et al., 2017; Yang et al., 2019). Further, Miller et al. (2022b) found in this sample that end of pre-K sustained attention and incongruent ANS accounted for unique variance in end of pre-K math performance in some, but not all levels of math ability. Therefore, the present study's findings should be interpreted with caution as kindergarten math achievement was not included as a moderator.

Implications

The study's findings support three main conclusions. Firstly, mathematical knowledge at the end of pre-K is a strong predictor of math achievement in kindergarten for children who entered pre-K with limited mathematical knowledge, indicating that math assessments at the end of pre-K may be used to identify students at-risk for math difficulties in kindergarten. Additionally, end of pre-K print knowledge predicts kindergarten math achievement, underscoring the need to provide high-quality math and early literacy instruction in pre-K to ensure that children enter kindergarten with the prerequisite academic knowledge they need to build upon and develop their skills. Thirdly, further research is needed to examine how children with different levels of math ability utilize different aspects of EF while learning and engaging in different types of mathematical tasks beyond numbers and operations, which was the math outcome in the current study.

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APPENDIX A

Table A1

Intercorrelations Between Variables

	1	2	3	4	5	6	7	8	9	10
1. TEMA-3 scaled score at kindergarten	--									
2. Age at kindergarten	-.352**									
3. TEMA-3 scaled score at end of pre-K	.723**	.275**	--							
4. Letter-Word identification	.251**	.139*	.299**	--						
5. Phonological awareness	.540**	-.296**	.540**	.298**	--					
6. Incongruent ANS acuity	.103	.104	.227**	.196**	.110	--				
7. Sustained attention	.096	.164**	.237**	.171**	.130*	.276**	--			
8. Inhibition	.281**	.179**	.284**	.341**	.168**	.191**	.307**	--		
9. Working memory	.163**	.145*	.247**	.182**	.089	.179**	.213**	.265**	--	
10. Matrix reasoning	.230**	-.026	.226**	.184**	.077	.95	.141*	.235**	.172**	--

Note. TEMA-3 = Test of Early Mathematics Ability, 3rd edition. ANS = approximate number system.

*p<.05 ***p* < .01