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Associations between executive function and early math and literacy skills in preschool children

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Abstract

The current study directly compared the magnitude of associations between executive function (EF) and math versus literacy and investigated whether they differed by age within the preschool years. Participants were 92 typically developing, preschool children in the United States ($M_{\text{age}}=58.53$ months; 47.8% Female; 58.7% White; 29.3% Non-White). Children completed a developmentally sensitive battery of direct EF assessments, math and literacy achievement tests, and IQ tests. Results showed an EF Composite was associated with math, but not literacy, after controlling for age, verbal and nonverbal IQ, and socioeconomic status. Extending prior work to a younger age, we examined whether the association between EF and academic achievement was moderated by age but found no significant interactions. These findings support the link between EF and math before kindergarten and indicate a similar magnitude of associations in younger and older preschoolers.

Keywords

Executive function; Mathematics; Literacy; Preschool; Academic achievement

1. Introduction

Over the last two decades, convergent evidence has linked individual differences in executive function (EF) skills to concurrent and predictive academic achievement in racially/ethnically diverse and international samples (e.g., Allan et al., 2014; Alloway & Alloway, 2010; Cadima et al., 2015; De Franchis et al., 2017; Thorell et al., 2013). EF skills, which are higher-order neurocognitive processes required to engage in goal-directed behavior, are typically described in terms of three related components: working memory, inhibitory

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Stephanie M. Carlson is a Co-founder and holds equity in Reflection Sciences, Inc., which has licensed the Minnesota Executive Function Scale (MEFS) from the University of Minnesota. These interests have been reviewed and managed by the University of Minnesota in accordance with its Conflict of Interest policies.

control, and cognitive flexibility (Miyake & Friedman, 2012). EF skills are considered to be culturally universal, such that they support goal-directed behaviors across cultures, even if the goals themselves vary (Obradović & Willoughby, 2019). Given EF, early math, and emergent literacy skills serve as precursors for later academic success, understanding the intricacies of how EF is associated with academic domains is of international interest for researchers, educators, and global initiatives on early education (Duncan et al., 2007; UNICEF, 2021).

The preschool years are an important time to study these interrelations because EF develops rapidly during this period. At the same time, foundational math and literacy skills are being acquired. Understanding of basic numerical concepts, letter recognition, and word identification allows for higher-level mathematical problem solving and reading. Similarly, providing adequate opportunities for EF growth in preschool is important because this is a window of time in which EF skills are hypothesized to be highly malleable (Carlson et al., 2013; Zelazo & Carlson, 2012). Therefore, it is necessary to continue to research the associations between EF and academic skills in preschool or earlier to inform early childhood education initiatives worldwide, including the United Nations International Children's Emergency Fund (UNICEF) and the organisation for Economic Co-operation and Development (OECD, 2020; UNICEF, 2021).

Few studies have directly compared the magnitude of associations between EF and different academic subjects within the preschool period, which is when the building blocks for school success are being established. Moreover, to our knowledge, work is needed to examine how the relations between EF and academic achievement might vary *within* preschool as a function of age. Age could matter because EF skills might play a more prominent role in academic tasks if they are more or less developed. For instance, EF skills might play a more prominent role in academic tasks for younger preschoolers than older preschoolers because the academic content is more novel. Thus, these children might rely on higher-order cognitive skills more than prior academic knowledge or experience to demonstrate their learning. Conversely, it is also possible that EF skills play a more prominent role in academic tasks for older preschoolers because more developed EF skills might make it possible to implement more effective strategies or better coordinate EF components during an academic task. Therefore, in addition to comparing the association between EF and math and EF and literacy, we examined the extent to which relations between EF and academic achievement domains differed as a function of child age.

1.1. Executive function and academic skills

Concurrent and predictive associations between EF and math and EF and literacy have been supported by international research in countries, such as Germany, Portugal, India, Kenya, Ghana, China, Taiwan, Italy, the United Kingdom (U.K.), and the United States (U.S.; Bhavnani et al., 2019; Cadima et al., 2015; De Franchis et al., 2017; Gathercole et al., 2004; von Suchodoletz & Gunzenhauser, 2013; Wanless et al., 2011; Willoughby et al., 2019; Zhang & Rao, 2017). There is also convergent evidence of positive associations between EF and early academic skills in cross-cultural research, indicating this finding is likely not culture or country specific (Wanless et al., 2011). A meta-analysis on

concurrent associations between inhibitory control and academic skills in the preschool and kindergarten years from a combination of U.S. and non-U.S. samples found a stronger association between inhibitory control and math skills ($r = 0.34$), than inhibitory control and literacy skills ($r = 0.25$; Allan et al., 2014). However, covariates were not accounted for, and inhibitory control is only one component of EF skills. Some individual studies also report stronger relations between EF and math versus EF and literacy skills in early childhood when measuring EF as a composite or latent variable (e.g., Schmitt et al., 2017; Welsh et al., 2010) and as individual EF components (Nguyen & Duncan, 2019), but statistical differences in the magnitude of these relations are not consistently tested. On the other hand, well-powered studies of U.S. children and a meta-analysis with samples from multiple countries have called this finding into question by reporting similarly moderate relations between EF and math as between EF and literacy at various ages (Best et al., 2011; Jacob & Parkinson, 2015). Thus, further study on this topic is needed amid inconsistent results.

Longitudinal research has found earlier EF skills predict later math and literacy skills, even after controlling for academic performance at an earlier time point (Wolf & McCoy, 2019). For example, Fuhs et al., 2014 found that EF skills at the beginning of preschool predicted end of preschool literacy skills; however, beginning of preschool literacy skills did not predict end of preschool EF skills. This suggests a unidirectional, rather than a bidirectional relation, which is consistent with some other studies examining EF and literacy (Blair & Razza, 2007, Blair & Razza, 2007; Ponitz et al., 2009; Schmitt et al., 2014). EF skills predict later math, but there is mixed evidence on whether math also predicts later EF, (Cameron et al., 2019; Ellis et al., 2021; McKinnon & Blair, 2019). It is possible these inconsistencies in the literature are partially explained by variation in the directionality of these relations over time. For instance, Schmitt et al., 2017 found a bidirectional EF and math relation in preschool, but not kindergarten. Overall, variations in the relations between EF and math and EF and literacy indicate some of the mechanisms linking these sets of skills might differ.

Several explanations have been proposed regarding the differential associations between EF and math compared to EF and literacy. First, it is possible mathematics might place higher demands on EF skills than other academic domains due to the nature of the content (Bull et al., 2008; Schmitt et al., 2017). For example, vocabulary and knowing the names of letters might become more rote, rather than effortful after repeated practice, whereas when counting several items on a page even a more skilled counter might use their working memory to mentally keep track of which items were already counted. It is also possible that effortful tasks in both domains invoke EF skills, meaning that there are some literacy and math tasks with higher and lower EF demands (e.g., addition versus rote counting) that vary based on individual factors, such as whether one is still learning the skill. In other words, EF might play a smaller role in “exercising” academic skills once they have been learned. Next, in reference to literacy, some have proposed early childhood literacy assessments themselves might be more knowledge-based, meaning demands are primarily placed on retrieving previously acquired factual information. Conversely, mathematics assessments might invoke greater EF skills to mentally transform elements of the problem, shift between different aspects of the problem, and inhibit distracting information (Blair et al., 2015; Schmitt et al., 2017). Further, instruction could play a role. Reports from early childhood education teachers in the U.S. indicate more time is spent on early literacy instruction than early

mathematics instruction, on average (Early et al., 2010; Engel et al., 2013). It is possible children with higher EF skills might independently (or through teacher encouragement) seek out more complex mathematics activities during free choice play because they have the cognitive skills to support completion of these tasks (Fuhs et al., 2014; Schmitt et al., 2017). Lastly, there could be some similarity in the factors contributing to the EF and math and EF and literacy relation, in that EF could relate to the learning process more broadly by being one of many domain-general cognitive skills needed to successfully learn and/or influencing a child's ability to pay attention, sit still, and/or resist distractions in the classroom (Duckworth & Carlson, 2013).

1.2. Moderating role of age

Most of the research examining whether the association between EF and academic achievement might vary by child age is derived from meta-analyses. For instance, Allan et al., 2014 meta-analytically examined whether child grade (preschool versus kindergarten) was a moderator of the association between inhibitory control and academic achievement (math and literacy), but the grade-level effect was non-significant. Other meta-analyses have focused on the relation between specific academic skills and EF components. For instance, before 4th grade, the relations between reading and various domains of working memory (e.g., visuospatial, verbal) were similar in magnitude; however, at or beyond 4th grade, verbal working memory was more strongly related to reading than visuospatial working memory (ages 4–80 years; Peng et al., 2018). Meta-analytic age effects have also been examined by comparing children versus adolescents/adults or combining several grades (e.g., grades 1–3), but age is rarely examined categorically within a particular period (e.g., within a grade) or continuously. This variation in how age is operationalized might contribute to inconsistency in whether age effects emerge or not. Additionally, when pooling studies conducted across various age groups, it is impossible to determine if the findings can be explained by heterogeneity in samples, measures, or if the nature of the relation truly varies (Peng & Kievit, 2020). One way to begin disentangling these possibilities is to examine whether there are age effects in individual cross-sectional or longitudinal studies, some of which will be reviewed here.

Similar to the mixed meta-analytic findings, the findings from single studies do not provide clear evidence on whether the relations between EF and academic skills vary or remain stable over time. For example, in a large, nationally representative U.S. sample of children ages 5–17 years, multiple correlations between EF and math and EF and literacy slightly increased in strength with age, with substantial increase from 5 to 6 years of age (Best et al., 2011). Overall, there was a decrease or plateau (depending on the EF subtest) in these relations until another spike in later childhood for multiple EF subtests and academic skill correlations. Similarly, Stipek & Valentino (2015) found that increases in working memory predicted an increase in academic skill growth in earlier years (ages 5–9) but a negative relation emerged in later years (ages 10–14), such that growth in working memory was associated with slower academic skill growth. One explanation proposed by the authors is that many children were near ceiling on the working memory task at age 11 and those who were still improving on this task in the later years might have had lower scores at the start of the study. Other studies report the relations between EF and academic skills are relatively

stable, as reported with samples 5–20 and 8–25 years of age (Cragg et al., 2017; Kahl et al., 2021). Although these studies offer initial insight into possible age-related variation in the association between EF and academic achievement, there is a lack of literature within the preschool years specifically and age is rarely examined continuously.

There is a critical need for research examining age effects within preschool because in these years there is rapid EF and academic development. It is possible that as EF skills grow from 3 to 5 years of age, children are able to rely more heavily on EF skills during academic tasks. Thus, as children's EF skills develop, they might be better able to implement strategies during academic tasks, resulting in better academic performance. If the relations between EF and academic achievement grow stronger as EF skills develop and children become accustomed to schooling, we would expect the association between EF and academic achievement to be stronger for older preschoolers than younger preschoolers. Conversely, it is also possible the association between EF and academic skills is stronger for younger children because this is when the earliest foundational skills in academic domains are likely being acquired. It might be that EF skills are more strongly relied on when academic tasks are more novel because they have less experience with academic content and/or problem solving than their older preschool classmates. Finally, it is possible EF and academic skills are not moderated by age, and that the relation is relatively stable across the preschool years. In the current study, we were motivated to extend prior work (e.g., Best et al., 2011) to the preschool years to test these competing possibilities in a younger sample.

1.3. Components of executive function

Although there is substantial evidence to link EF to math and literacy skills, there are still some inconsistencies in the literature regarding how EF is conceptualized. Some studies examine EF as a unitary construct, whereas others examine EF components separately.

Multiple inconsistencies are found in studies that attempt to examine the associations between separate EF components and academic skills. For instance, Espy et al. (2004) found inhibitory control was the only component that uniquely predicted early math skills in a sample of 2- to 5-year-old children. Conversely, a meta-analysis found a positive association between cognitive flexibility and math skills that did not vary by child age or grade (preschool/kindergarten versus primary/grade school; Yeniad et al., 2013). Additionally, studies with preschool samples from the U.S., U.K., and China found working memory was a predictor of early math skills (Alloway & Alloway, 2010; Lan et al., 2011; Purpura & Ganley, 2014). Similar inconsistencies have been reported for EF and literacy, such that some studies found inhibitory control was associated with literacy skills, whereas others did not (for review see: Traverso et al., 2022). These inconsistencies in findings make it difficult to tease apart relations between EF and domains of academic achievement in preschool.

Examining the unique contribution of multiple EF components simultaneously might yield inconsistent findings because EF skills in preschool appear to be more of a unified, domain-general process, rather than separable components (Wiebe et al., 2008, 2011). In older children and adulthood, there is evidence for models with multiple factors being a better fit (e.g., Miyake & Friedman, 2012). This is consistent with the general pattern of increasing

functional specialization of neural systems, which are initially rather undifferentiated and become more specialized over the course of development (Johnson & Munakata, 2005).

On the other hand, these discrepancies in the literature could also be due to measurement error. Many studies rely on a single task to represent an EF component or EF globally, making it more difficult to identify and reduce measurement error. Studies that administer a battery of EF tasks and create a composite in an attempt to reduce measurement error might have greater likelihood of being replicated. Additionally, concurrent associations between individual EF tasks and academic achievement are modest in magnitude $r_s = 0.3\text{--}0.45$ (Blair & Razza, 2007; Bull et al., 2008), whereas the associations between EF composites and academic achievement tend to be stronger, $r_s = 0.4\text{--}0.6$ (Brock et al., 2009; Espy et al., 2004; Welsh et al., 2010; Willoughby et al., 2011).

1.4. Confounding variables

Finally, some prior studies failed to consider covariates that likely account for a substantial amount of variance, such as IQ, despite evidence suggesting EF and IQ are moderately correlated (Brydges et al., 2012). Some studies also did not account for background characteristics of the children, including parent education or family income. A measure of socioeconomic status (SES) is important to control for because studies in both high- and low-income countries (Fernald et al., 2011; Hackman et al., 2015) and a meta-analysis have reported small to medium sized effects of SES disparities in EF skills (Lawson et al., 2018). There is also a documented association between SES and academic achievement (Sirin, 2005). Importantly, in various U.S. samples, EF skills mediate the association between SES and academic achievement across childhood, suggesting EF skills may partially explain the link between SES and academic skills (Crook & Evans, 2014; Lawson & Farah, 2017; Raver et al., 2013; Waters et al., 2021). Therefore, SES is a possible confound when not included as a covariate.

Evidence suggests that EF is a more feasible target of change via intervention than SES, parental education, or lived experiences that are often relatively static (Espinet et al., 2013). This is partially why international interest in EF development within an educational context is continuing to grow. Thus, there is an immense need for rigorous replication and extension of work linking EF to domains of academic achievement because this work can inform early childhood policies and practices.

1.5. The current study

The current study has four primary aims: (1) to examine the association between EF skills and early math achievement, (2) to examine the association between EF skills and early literacy achievement, (3) to examine if the association between EF and math is stronger in magnitude than EF and literacy, and (4) to determine whether relations between EF and academic achievement vary as a function of child age within a sample including 4- and 5-year old children in the U.S. Given the theoretical and empirical links between EF and academic achievement, we hypothesized EF would be positively associated with math and literacy skills. We further hypothesized stronger relations between EF and math than EF and literacy. Additionally, we hypothesized age would moderate the relations between EF

and academic achievement. We aimed to test competing hypotheses, either that EF would be more strongly associated with academic achievement in younger preschool children or in older preschool children. To our knowledge, aim 4 has not yet been examined within the preschool years, and as such this was a strong motivator for the current study.

2. Methods

2.1. Participants

Ninety-two preschool aged children (44 females) participated in this study ($M_{\text{age}} = 58.53$ months, $SD = 5.5$, range = 48–71 months). Participants were recruited from 15 preschools in a metropolitan midwestern U.S. city and surrounding counties. No child had yet begun formal schooling (which is kindergarten in the U.S.). Participant eligibility criteria included being between 48–71 months of age, English speaking, no premature birth, no known developmental delays or disorders, and no physical impairments that affect vision or hearing. An additional 37 children started the study but were excluded, mainly due to the child not meeting exclusionary criteria or the parent not confirming eligibility ($n = 26$); other reasons were noncompliance/inability to complete the tasks ($n = 4$), or inability to complete sessions in a timely manner due to attendance/child leaving the center ($n = 7$). There were also twins that participated in this study. For these analyses, one child from the twin pair was randomly selected to be included in the analytic sample.

A little over half the children in this sample were White, non-Hispanic (58.7%), with an additional 12% Black, 10.9% Bi-racial, 3.3% Asian, 2.2% Hispanic, 1.1% Native American/Alaska Native, and 12% missing data. Around one-third of families reported an annual income of \$200,000 or more (29.3%); 10.9% earned \$175,000-\$199,999; 9.8% earned \$150,000-\$174,999; 4.3% earned \$125,000-\$149,999; 8.7% earned \$100,000-\$124,999; 4.3% earned \$75,000-\$99,999; 2.2% earned \$50,000-\$74,999; 13% earned \$25,000-\$49,999; 3.3% earned less than \$25,000; and 14.1% had missing data. Approximately half of the participants in this sample had at least one caregiver that held a graduate or professional degree (53.3%), an additional 3.3% with some graduate school or professional degree, 18.5% with a Bachelor's degree, 9.8% with some college, 1.1% with a high school diploma, 2.2% with a general education equivalency degree, and 12% missing data.

2.2. Procedure

Participants were recruited through their preschool program as part of a larger short-term longitudinal study designed to examine the role of EF in learning. Only relevant assessment data from baseline and posttest (approximately two weeks later) were considered for this study. The data from the posttest used in this study were not expected to be influenced by the instructional approaches used in the larger experiment. Nonetheless, experimental manipulations were accounted for statistically to ensure condition assignment was not contributing to the association between the variables of interest in this study.

A letter explaining the study was sent home by schools to caregivers of children ages 4- or 5-years-old. A trained research assistant obtained consent from interested families at the school pick-up times. At this time, parents were asked to complete a demographic

questionnaire, which was later sent to them digitally via Qualtrics or a paper copy was sent home with their child.

Data from a battery of cognitive tasks children completed in two sessions (average of 15 days between sessions) were considered for this study. Trained assessors tested children on three EF tasks: Minnesota Executive Function Scale, Backward Word Span, and the Statue Task, two subtests of the Woodcock Johnson III-NU Tests of Achievement (Letter-Word Identification and Applied Problems), and two subtests of the Stanford Binet Intelligence Scales for Early Childhood (5th Ed.; Verbal Knowledge and Nonverbal Fluid Reasoning). The EF tasks were completed at the baseline session and the academic achievement and IQ tests were completed at posttest. The tasks were selected based upon developmental appropriateness, sensitivity, psychometric properties, and fit for the larger study from which these data were drawn. Children were compensated with stickers at each session and a small toy after completing the study.

2.3. Measures

2.3.1. Minnesota executive function scale—The Minnesota Executive Function Scale (MEFS App™; Carlson & Zelazo, 2014) is a standardized measure of EF administered on a tablet. This task is reliable, valid, and normed based on a sample of over 52,000 typically developing children ages 2–17.9 years old (Carlson, 2021). The MEFS is an adaptive task in which the recommended starting level is based on age. In total, there are seven levels of increasing difficulty. Children were seated next to an experimenter with the tablet in front of them. Participants were asked to sort virtual cards based on different dimensions (e.g., color or shape) by dragging them into the boxes on the screen. Children continued to move up a level until they failed or completed Level 7. If the child did not pass the starting level, they moved down a level, and continued to move down until they passed or completed Level 1. The MEFS takes approximately 5 min. Reliability and validity of this task has been established and reported extensively elsewhere (e.g., test-retest reliability is 0.73; Carlson, 2021). An algorithm within the MEFS app takes trial accuracy and reaction time into account to calculate total scores for each participant (range = 0–100); these raw scores were used in analyses.

2.3.2. Backward word span—Backward Word Span (BWS) assesses verbal working memory. In BWS, children were asked to repeat a list of single-syllable, non-semantically related words stated by the experimenter in reverse order (Carlson et al., 2002). A puppet demonstrated repeating a word sequence stated by the experimenter to help children learn the game (e.g., The experimenter said “book, cup” and the puppet said, “cup, book”). This was followed by a practice trial, in which the child was given feedback and up to four tries before moving on to the test trials. The test trials started with a two-word level and increased by one word at each level (3, 4, 5, 6, and 7 words). Children moved up a level after each correct sequence they repeated. If the child incorrectly recited a sequence, they were given another sequence of the same length. The task was terminated after three consecutive failures within a level. This task takes approximately 5 min to complete and has been found to be correlated with other EF measures in the preschool and kindergarten years (Bernier et

al., 2015; Bierman et al., 2008). Scores correspond to the highest number of words the child could successfully recite in reverse order (possible range = 1–7).

2.3.3. Statue task—The Statue Task is a subtest of the NEPSY (Developmental NEuroPSYchological Assessment) standardized battery and was designed to assess motor persistence and inhibition of impulses for children 3–6 years of age (Korkman et al., 1998). Children were asked to maintain a statue-like pose, remain silent, and keep their eyes closed until the experimenter said, “Time’s up!” Over the course of 75-seconds, the experimenter produced distractors (e.g., knock on the table twice, cough) at set times to tempt the child to react. Coding included 15 5-second segments. In each segment, the experimenter recorded the presence of body movements, vocalizations, and/or eye opening. Children received two points for each 5-second segment they remain silent in statue position with their eyes closed. Segments with one type of error received one point. Segments with two or three errors received 0 points. If children started the task, then quit before the 75-sec period was up, they got 0 s for all the remaining time intervals. Children received a score between 0 and 30. Test retest reliability for this task is high (0.81 for ages 3–4 and 0.79 for ages 5–6; (Brooks et al., 2009).

2.3.4. Woodcock-Johnson III-normative update—The Letter-Word Identification and Applied Problems subtests of the Woodcock-Johnson III-Normative Update (WJ III-NU) were used as measures of academic achievement (Woodcock et al., 2001). This task is appropriate for ages 2–90 years and reliability and validity have been established (McGrew et al., 2007). The Letter-Word Identification subtest is a measure of emergent literacy skills. This subtest consists of identifying lower- and upper-case letters and words and reading words on the page. The Applied Problems subtest is a measure of mathematical reasoning. It consists of solving numerical and spatial problems presented with accompanying pictures of images. Difficulty increases as the subtests progress. Each subtest was complete when the child answered six consecutive questions incorrectly. Standard scores for each subtest were used in analyses ($M = 100$, $SD = 15$). The two subtests together take approximately 15 min.

2.3.5. Stanford Binet intelligence scales for early childhood (5th Edition)—The Verbal Knowledge and Nonverbal Fluid Reasoning subtests of the Stanford-Binet Intelligence Scales for Early Childhood (5th Edition) were administered to estimate child intelligence (Roid, 2003b). This task is valid, reliable, and appropriate for children ages 2 and up (Roid, 2003a). Starting items vary based on the age of the child. The Verbal Knowledge subtest measures verbal ability and consists of naming objects and pictures and defining words of increasing difficulty level. The Nonverbal Fluid Reasoning subtest measures nonverbal problem solving. Children were asked to identify patterns in series of objects and pictures. Each subtest was complete when the child received a 0 on four consecutive items. Standard scores for each subtest were used in analyses ($M = 10$, $SD = 3$). The two subtests together take approximately 10 min.

2.3.6. Family information questionnaire—Caregivers were asked to complete a brief demographic questionnaire to gather information pertaining to child age, race/ethnicity of the caregiver(s) and child, family income, and highest education level of caregiver(s).

Caregivers also provided information pertaining to relevant exclusionary criteria. This was completed electronically via Qualtrics or on paper.

3. Results

3.1. Missing data

There were some missing data for the variables of interest in this study: family income (14%), caregiver highest education level (12%), SES Composite (14%), Nonverbal IQ (2%), Verbal IQ and EF Composite (each 4%), WJ Applied Problems (5%), WJ Letter Word (3%), Statue Task (3%), and BWS (2%). The mechanism of missingness was explored and we concluded data were missing at random. Thus, it was possible to estimate missing data based on other variables within the data set. We conducted 10 iterations of multiple imputation in R using the MICE package (van Buuren & Groothuis-Oudshoorn, 2011). Demographic information, predictors, and outcome variables were used to inform the imputation process. The pooled imputed dataset was used for analyses.

3.2. Descriptive analyses

Descriptive statistics on non-imputed data are displayed in Table 1. The Statue task was the only variable that depicted a slight skew ($\text{skew} < -1$). Correlations among EF, academic achievement, and IQ conducted on the imputed dataset are displayed in Table 2. We examined the correlations and conducted a Principal Components Analysis (PCA) with the individual EF tasks to determine if an aggregated EF variable was appropriate. The bivariate correlations on the imputed data among the MEFS, Statue Task, and BWS ranged from $r(90) = 0.26$ to 0.42 . The PCA on the non-imputed dataset suggested a one factor solution best fit the data based on a scree plot. The component loadings ranged from 0.69 to 0.80 . Therefore, an EF Composite score for each participant was computed by averaging z -scores of the Statue, MEFS, and BWS tasks, and was used in all subsequent analyses. After imputation, the EF Composite was re-standardized to ease interpretation (Song et al., 2013). A composite score is preferred because it has the potential to reduce measurement error. Further, prior evidence suggests EF is a unitary construct in preschool (Wiebe et al., 2011), and creating a composite enabled us to examine EF holistically, on par with the way the literacy and math subtests of the WJ-NU III are given overall scores.

Due to the high correlation between caregiver education level and annual family income ($r = 0.55$), we computed an SES Composite by averaging the z -scores of these two variables representing distinct and interrelated dimensions of family background and included the composite as a covariate in subsequent models. After imputation, the SES Composite was re-standardized.

Additionally, participating children were nested in schools. To assess clustering at the school level, we computed intraclass correlations ($ICCs$) for both dependent variables (i.e., literacy and math scores). Literacy and math scores displayed substantial between-school level variability (unconditional $ICC = 0.35$ and $ICC = 0.48$, respectively). In response, we clustered the standard errors at the school level in subsequent analyses to reduce bias.

3.3. Main analyses

3.3.1. Associations between executive function and math—First, we examined whether EF was associated with math achievement in preschool. To do this, we conducted a hierarchical linear regression predicting WJ Applied Problems scores and clustered the standard errors at the school level. In the first block, we entered relevant covariates, including Age in Months, Nonverbal IQ, Verbal IQ, two variables related to the experimental condition the child was assigned to in the larger study, and the SES Composite. Although WJ and EF scores were not expected to vary by the randomly assigned experimental conditions of the larger study from which these data were derived, we included these in the model to ensure they were not contributing to the association between our key variables of interest. In the second block, we entered the EF Composite score. Consistent with the hypothesis, children with higher EF Composite scores achieved at higher levels on the WJ Applied Problems subtest ($B = 6.21$, $SE = 1.59$, $p < .001$). The covariates we included accounted for 45% of the variance (on average across pooled imputed datasets) in early math skills. Adding EF to the model significantly accounted for an additional 12% of the variance (see Table 3).

3.3.2. Associations between executive function and literacy—We also examined whether EF was associated with literacy skills. To do this, we conducted a hierarchical linear regression predicting WJ Letter-Word Identification scores. In the first block, we entered the same set of covariates as in the previous model. In the second block, we entered the EF Composite score. Despite the significant bivariate correlation ($r(90) = 0.29$), the EF Composite did not significantly predict WJ Letter-Word scores ($B = 4.07$, $SE = 2.31$, $p = .078$). The covariates in the first block accounted for 25% of variation (on average across pooled imputed datasets). Adding EF to the model accounted for an additional 6% of variation in emergent literacy skills, but this change was not significant at the 0.05 level (see Table 4).

3.3.3. Associations between executive function and each academic domain—Steiger's z -tests (Steiger, 1980) were used to examine whether the magnitude of the bivariate correlations between EF and math versus EF and literacy differed significantly. As expected, the correlation between the EF Composite and Applied Problems ($r(90) = 0.57$) was significantly larger than the correlation between EF and Letter-Word Identification ($r(90) = 0.29$), $z = 3.20$, $p < .001$.

3.3.4. Moderating role of age—Finally, we wanted to examine if the relation between EF and academic achievement differed as a function of age. Preliminarily, we examined the correlations between the EF Composite and WJ Applied Problems and WJ Letter-Word Identification for children of varying ages. We used the median Age in Months (58) to divide the participants into two groups: children who were younger ($n = 50$, age = 48–58 months; ~4-year-olds) and older ($n = 42$; age = 59–71 months; ~5-year-olds). We then looked at the correlations between EF and math and EF and literacy for younger and older children separately. As illustrated in Fig. 1 (Panel A), the correlations between EF and math and EF and literacy were stronger for the ~4-year-olds than the ~5-year-olds in the sample; however, there were no significant differences in magnitude of the bivariate correlations of EF and

math or EF and literacy for younger versus older children, according to Steiger's z -tests. For the sake of comparison with prior research, we plotted our results adjacent to those of Best et al., 2011; Fig. 1, Panel B), as their study began where ours ended, at age 5.

Next, we conducted parallel sets of regressions as described above in Sections 3.3.1 and 3.3.2 within each age subgroup. Similar to the whole group results, there were no significant relations between EF and literacy in subgroups of younger and older children. In contrast, the EF Composite was significantly associated with math after accounting for covariates for the younger ($B = 6.25$, $SE = 1.93$, $p = .001$), but not the older children ($p = .10$).

To further examine if Age in Months (as a continuous variable) moderated the EF and academic skill relations, we conducted hierarchical linear regressions predicting math and literacy. First, we conducted a hierarchical linear regression predicting WJ Applied Problems scores. In the first block, we entered child Age in Months, Nonverbal IQ, Verbal IQ, two variables related to the experimental design of the larger study, family SES Composite, and the EF Composite. In the second block, we entered the interaction term between the EF Composite and Age in Months. Next, we conducted a hierarchical linear regression predicting WJ Letter-Word Scores. The same variables were entered in block one and two. We did not find significant moderation by age in either of these models. Hence, although separate age group analyses suggested a stronger association between EF and math skills among 4-year-olds than 5-year-olds, there was no interaction effect, suggesting a more sensitive analysis using age as a continuous variable was nonsignificant.

4. Discussion

The primary aims of this study were to examine the unique associations between EF and early academic abilities and to investigate whether age moderated these relations in preschool children. The findings indicated EF skills were associated with math, but not literacy skills, controlling for age, IQ, and SES. Additionally, the association between EF and math was of stronger magnitude than that of EF and literacy, which is consistent with some previous studies (Allan et al., 2014; Blair & Razza, 2007; Fuhs et al., 2014). Further, we examined if the link between EF and academic achievement was moderated by age, such that the relations would be stronger for older or younger children but found no significant interaction effect. These findings indicate the relation between EF and math skills in the preschool period are robust and similar across ages 4 and 5 years, even after accounting for a host of covariates.

4.1. Executive function, math, and literacy

This study provided further empirical support for the documented relations between EF and early math (Clements et al., 2016; Ribner, 2020). Our results included both verbal and nonverbal IQ as covariates, which provides a more rigorous test of the association between EF and early math skills.

We were unable to replicate the finding that EF was significantly associated with literacy skills in preschool, despite including a commonly used literacy measure that has been associated with EF skills in prior work (e.g., Fuhs et al., 2014). As has been noted

by others, the skills assessed in WJ subtests change as children progress. In the Letter-Word Identification subtest, early items focus on print knowledge and then shift toward phonological awareness and word knowledge (Purpura et al., 2017). The stop rules of this task make it so that samples with varying ability levels are exposed to different categories of items (e.g., print knowledge versus word knowledge) and some of these skills are differentially associated with EF components (Purpura et al., 2017). Therefore, it is possible our findings differ from prior work due to variation in sample characteristics. It might also be that the association between EF and literacy is weaker than the association between EF and math and when we included covariates, such as IQ, that are not always accounted for, the association was no longer significant. We also statistically accounted for the nesting of children by school, which is not always done in school-based studies. It is possible that with this rigorous statistical test, we might have needed a larger sample size to detect an effect.

Additionally, the association between EF and early math skills was of significantly greater magnitude than the association between EF and literacy skills ($r_s = 0.57$ and 0.29 , respectively). This finding is consistent with some previous studies and meta-analyses of preschool and kindergarten children (Allan et al., 2014). It has been speculated this may be due to the nature of the content, such that early math content may invoke stronger EF demands, or greater time spent on instruction of literacy compared to math in early childhood classrooms. It could also be a function of the early literacy skill measured in this study. The relations between EF and literacy could be stronger during the learning process, whereas the skills invoked during basic letter-word identification might be more automatized by preschool in some children and still effortful for others (Blair & Razza, 2007; Fuhs et al., 2014). If we had measured a specific literacy skill, such as reading words, then the skill might be less automatized and invoke greater EF demands, on average, because this skill is possibly more effortful for many preschoolers. Unfortunately, we were unable to tease apart these possibilities here, but this should be examined in future work.

Other studies have found evidence that the associations between EF and math and EF and literacy are comparable in magnitude (Jacob & Parkinson, 2015). Although this was not the case here, some have argued that the association between EF and academic performance is comparable across subjects because EF plays a role in the learning process more generally. For instance, children with higher EF skills might be better equipped to maintain sustained attention on the teacher's lesson, which could partially explain why children with higher EF skills perform better on academic achievement tests. Our finding that EF is more strongly associated with math than literacy does not discount this possibility but suggests that some academic subjects may invoke greater EF demands than others, either during the learning process, on academic achievement tests, or both.

The current examination of these relations contributes to the study of EF and academic achievement in multiple ways. First, prior research varies in the way EF is defined and operationalized. Some studies decomposed EF into its components and examined how each component was associated with academic achievement, whereas other studies examined EF as a unitary construct. The differences in measurement make it difficult to interpret discrepancies within an age range. Our decision to examine EF as a unitary construct was driven by prior work showing one-factor models were more parsimonious than multi-factor

models in the preschool years (Wiebe et al., 2011). Further, our preliminary data suggested each EF task was tapping into the same construct; thus, creating an EF composite was appropriate. Second, here we examined the relations between EF and academic achievement above and beyond child IQ and family SES. Our findings strengthen support for the relations between EF and math by controlling for important covariates that are often not included in analyses, such as both verbal and nonverbal IQ, family SES, and accounting for nesting in schools.

4.2. Differential relations by age

Although some studies have examined if age moderates the relations between EF and academic achievement, more research was needed in the preschool years. Prior work investigated this effect by comparing preschool, school-age, and adolescent relations to one another (Jacob & Parkinson, 2015) or comparing preschool and kindergarten relations to one another (Allan et al., 2014). Conducting an examination of these relations within the preschool years was critical because it is the period in which EF develops most rapidly and foundational literacy and math skills are acquired. Our study attempted to fill this gap. We were unable to find support for our hypothesis that the relations between EF and academic achievement are moderated by age. One reason could be that our moderation analysis was underpowered to detect a small to moderate effect. Therefore, the lack of a significant moderation by age in the current study may be due to insufficient power, rather than a true absence of an age-related moderation. The correlations between EF and math and EF and literacy at varying age bands (displayed in Panel A of Fig. 1) and the significant EF and math relation in younger, but not older preschoolers in subgroup analyses, indicate there *might* be a stronger association between EF and academic skills for younger compared to older preschoolers. It is also possible varying operationalizations of age as continuous versus a categorical variable could be contributing to variation in these findings. These findings should be interpreted with caution and replication with a larger sample size that is powered to detect small effect sizes is needed.

It could also be that there is not a statistically significant moderating effect of age on the relations between EF and academic achievement within the preschool years. It is possible age plays a moderating role over the course of the lifespan, but not in the relatively narrow time frame studied here (48–71 months; Peng et al., 2018). When taken together with the correlations between EF and literacy ($r_s = \sim 0.30\text{--}0.32$) and EF and math ($r_s = \sim 0.31\text{--}0.39$) reported in Best et al. (2011) at age 5, our findings ($r_s = 0.31$ and 0.50 , for literacy and math, respectively) for older preschoolers appear to align (Fig. 1). Although, the younger preschoolers (~4 years) in our study had higher bivariate correlations ($r_s = 0.4$ and 0.68) between EF and academic skills than the 5-year-old children included in Best et al. (2011). It could also be that EF plays a stable role in academic skills throughout the school years (or the lifespan; Morgan et al., 2019). Both our study and Best et al. (2011) were cross-sectional, whereas a multi-year longitudinal examination of the relations between EF and academic achievement beginning in preschool would help to tease apart these possibilities.

4.3. Limitations and future directions

The current study had several strengths, including multiple direct assessments of child EF skills, use of an EF composite to potentially reduce measurement error, and inclusion of relevant covariates that have been excluded in some prior work. Despite this, there were a few limitations we must acknowledge. First, our moderation analysis was underpowered, and further examination of age-related differences in the association between EF and academic achievement in preschool is warranted. Second, this study was cross-sectional, so future longitudinal studies are needed to examine the co-development of EF and academic achievement. Third, these findings are correlational in nature so future work should pursue experimental methods to understand the associations between EF and academic skills. Fourth, our sample was predominantly middle to high SES and was geographically limited to children living in or around a metropolitan midwestern U.S. city. Future studies should attempt to replicate these findings with a larger, more socioeconomically representative sample and in other geographic regions.

Further, achievement tests were not broken down into separate skills, such as phonological awareness for literacy or patterning for math. Some previous studies examined the links between EF and specific skills, including mathematical conceptual understanding and EF in older children and adults (Cragg et al., 2017) and EF and distinct numerical skills in three to six year old children (Chan & Scalise, 2022). This is a promising future direction to extend this line of work that could be important for informing future academic interventions because they tend to focus on a specific skill or set of skills (e.g., counting). Finally, future researchers should attempt to examine the associations between EF and academic achievement in cross-cultural work. Previous cross-cultural work suggests the associations between EF and academic achievement exist in many high and low-income countries, but that there might be cultural variation regarding which EF components are the strongest predictors of academic skills across the lifespan (Georgiou et al., 2020).

5. Conclusions

The present study extended prior work by providing a rigorous examination of the relations between EF and achievement, including age effects, in the preschool years. To our knowledge, this is the first study to investigate the possibility of an age-related moderation in the association between EF and academic achievement within preschool; however, this interaction did not reach significance. Additionally, we replicated the moderate positive association between EF and early math, but not literacy. This could suggest the covariates that were not included in some prior studies were accounting for a substantial amount of variance in literacy, but more research is needed to determine if this is the case.

Overall, these findings on the relations between EF and academic skills have educational implications for academic learning in classroom contexts. The evidence that EF and math are positively correlated can be used to inform instruction, curricula, and activities in early childhood classrooms. Specifically, when developing educational math materials, it might be important to account for both the math and EF demands to ensure the content is appropriately challenging. During instruction, teachers can use scaffolding to adjust the EF, math, or both EF and math demands of the activity. These avenues for modifying the

demands of the activity or the instruction to meet the needs of the learner(s) for both math and EF may be one way to increase effectiveness of classroom activities. These findings can also inform future studies aiming to disentangle how EF plays a role in academic tasks, and which specific academic skills (e.g., patterning, reading) demand EF skills.

Importantly, this area of research is of international significance. There is worldwide interest from researchers (e.g., *Creating Connections in Child Development - Web Series*; (Bayley et al., 2022) and organizations (OECD, 2020; UNICEF, 2021) both on the development of EF skills and their relation to academic skills. This work in combination with future studies can be used to inform educational practices and policies in early childhood on a global scale.

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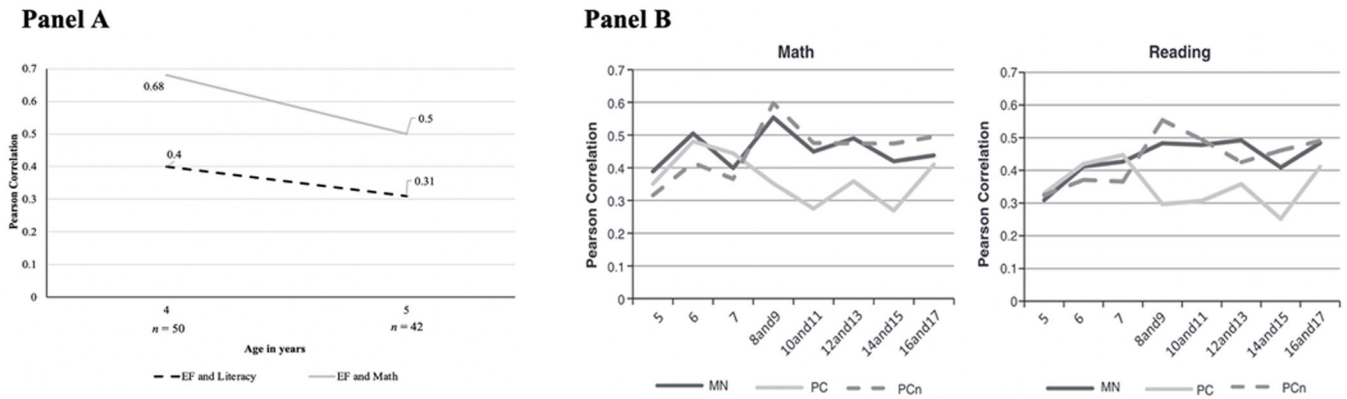


Fig. 1. Bivariate Pearson Correlations Between Executive Function (EF) and Math and Literacy Achievement in Preschoolers (Panel A) and Older Children and Adolescents (Panel B) *Note.* Panel B presents various EF subtests including, MN = Matching Numbers, PC = Planned codes, and PCn = Planned Connections. Panel B is Reprinted from Learning and Individual Differences, 21(4), J.R. Best, P.H. Miller, and J.A. Naglieri, “Relations between executive function and academic achievement from ages 5 to 17 in a large, representative national sample,” Page 334, Copyright (2011), with permission from Elsevier.

Table 1

Descriptive Statistics for Child Executive Function, Academic Achievement, and Intelligence.

	<i>N</i>	<i>M</i>	<i>SD</i>	Sample Range
Age in Months	92	58.5	5.5	48 – 71 months
EF Composite	88	0.1	0.7	–1.9 – 1.6
MEFS	92	48.8	16.6	11 – 91
Statue Task	89	21.4	8.6	0 – 30
Backward Word Span	89	2.0	0.8	1 – 3
WJ Letter Word ID	89	103.5	13.0	69 – 141
WJ Applied Problems	87	110.2	12.7	70 – 137
Verbal IQ	90	9.8	2.4	3 – 15
Nonverbal IQ	88	10.9	3.7	1 – 19

Note. Non-imputed data were used for these analyses. EF = Executive Function. MEFS = Minnesota Executive Function Scale. WJ = Woodcock-Johnson.

Table 2
 Bivariate (bottom left) and Partial (top right) Correlations Between Demographic Variables, Predictors, and Outcome Variables (N = 92).

Measure	1	2	3	4	5	6	7	8	9
1 BWS	–	.23*	.31**	.15	.22*	.41**	.49**	.35**	.73**
2 Statue Task	.30**	–	.16	.15	.27**	.09	.29**	.19	.67**
3 MEFS	.42**	.26*	–	.26*	.32**	.34**	.54**	.29*	.69**
4 Nonverbal IQ	.14	.14	.24*	–	.33**	.35**	.41**	.21	.27*
5 Verbal IQ	.27*	.31**	.36**	.32**	–	.20	.50**	.46**	.39**
6 Letter Word ID	.35**	.06	.24*	.35**	.17	–	.53**	.39**	.40**
7 Applied Problems	.48**	.29**	.50**	.41**	.50**	.51**	–	.51**	.63**
8 SES Composite	.35**	.20	.30**	.21	.47**	.38**	.51**	–	.40**
9 EF Composite	.77**	.70**	.76**	.24*	.42**	.29**	.57**	.38**	–

Note. Imputed data were used for these analyses. Partial correlations controlled for child Age in Months. BWS = Backward Word Span. MEFS = Minnesota Executive Function Scale. SES = Socioeconomic Status. EF = Executive Function.

* $p < .05$

** $p < .01$.

Table 3

Regression Analyses Predicting Applied Problems Scores (N = 92).

Variable	<i>B</i>	<i>SE(B)</i>	<i>t-value</i>	\bar{R}^2	\bar{R}^2
Block 1					
Age in Months	-0.01	0.31	-0.04	0.45	
Nonverbal IQ	1.05	0.39	2.67**		
Verbal IQ	1.52	0.71	2.15*		
Experimental Condition 1	-6.04	2.97	-2.03*		
Experimental Condition 2	-4.17	2.99	-1.39		
SES Composite	4.55	1.66	2.74*		
Block 2					
Age in Months	-0.51	0.28	-1.79	0.57	0.12**
Nonverbal IQ	0.82	0.32	2.57*		
Verbal IQ	0.99	0.47	2.11*		
Experimental Condition 1 ^a	-5.02	2.78	-1.81		
Experimental Condition 2 ^b	-2.39	2.57	-0.93		
SES Composite	3.13	1.64	1.91		
EF Composite	6.21	1.59	3.90**		

Note. Standard errors are clustered at the school site level.

^aDummy variable for random assignment to direct instruction learning condition in larger experiment.

^bDummy variable for random assignment to discovery-based instructional sessions. Control condition is the reference group.

* $p < .05$

** $p < .01$.

Table 4

Regression Analyses Predicting Letter-Word Identification Scores (N = 92).

Variable	<i>B</i>	<i>SE(B)</i>	<i>t-value</i>	\bar{R}^2	\bar{R}^2
Block 1					
Age in Months	-0.31	0.23	-1.35	0.25	
Nonverbal IQ	1.00	0.47	2.11*		
Verbal IQ	-0.40	0.60	-0.67		
Experimental Condition 1	1.01	2.82	0.36		
Experimental Condition 2	1.35	2.39	0.56		
SES Composite	4.67	2.09	2.23*		
Block 2					
Age in Months	-0.63	0.24	-2.60**	0.31	0.06
Nonverbal IQ	0.85	0.40	2.12*		
Verbal IQ	-0.75	0.44	-1.69		
Experimental Condition 1 ^a	1.67	2.78	0.60		
Experimental Condition 2 ^b	2.52	2.22	1.14		
SES Composite	3.73	2.39	1.56		
EF Composite	4.07	2.31	1.76		

Note. SES = Socioeconomic Status. EF = Executive Function. Standard errors are clustered at the school site level.

^aDummy variable for random assignment to direct instruction learning condition in larger experiment.

^bDummy variable for random assignment to discovery-based instructional sessions. Control condition is the reference group.

* $p < .05$

** $p < .01$.