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Bidirectional and co-developing associations of cognitive, mathematics, and literacy skills during kindergarten

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ABSTRACT

This study of children from two U. S. states examined associations among four cognitive and academic skills: executive function (EF), visuo-motor integration, mathematics assessed with applied problems, and letter-word knowledge. Before (T1) and after (T2) kindergarten, children (N = 555) were assessed using the Head-Toes-Knees-Shoulders (HTKS) EF task, the Beery-Buktenica test of Visuo-motor Integration (Beery VMI), and Woodcock-Johnson subtests of Applied problems and Letter-word identification. Bidirectional analyses showed that all T1 skills predicted at least one other skill, with T1 HTKS and T1 Applied problems predicting all skills. In addition, improving from T1 to T2 in Applied problems was associated with improvements in all skills using random effects analyses, based on differences between children nested in kindergarten classrooms. This overall pattern of results was confirmed using fixed effects analyses, which examined only within-child variability. We conclude that multiple skills undergird early mathematics learning and vice versa.

Introduction

Despite early curricular emphases on academic skills (Bassok, Latham, & Rorem, 2016), cognitive skills are also important for school readiness, including early mathematics and literacy achievement (Duncan et al., 2007; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). For example, executive function (EF)—the cognitive processes that enable children to focus and shift their attention, to remember instructions, and to inhibit impulses (Garon, Bryson, & Smith, 2008) –and another cognitive process involving fine motor and spatial skills, called visuo-motor integration, each help set the stage for learning (Blair & Raver, 2015; Carlson, Rowe, & Curby, 2013; Fuhs, Nesbitt, Farran, & Dong, 2014; Grissmer et al., 2010; Kim, Duran, Cameron, & Grissmer, 2017; Son & Meisels, 2006). Research shows strong support for *co-development* where cognitive and academic skills emerge together (Decker, Englund, Carboni, & Brooks, 2011; McClelland & Cameron, 2018; Roebers & Jäger, 2014; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). Additionally, cross-domain associations between cognitive and academic skills mean there are interrelations among the processes that enable children to successfully complete learning tasks and gain academically (Cameron, Brock, et al., 2015; McClelland & Cameron, 2018).

Co-development makes sense given how heavily EF is needed when learning any new academic skill (Blair, Protzko, & Ursache, 2011). Similarly, visuo-motor processes are prevalent in reading and writing, as well as spatial and numeric processes inherent in mathematics. In other words, early childhood numeracy and literacy skills draw on an underlying foundation of cognitive processes, such as decoding letter and number symbols, attending to tasks and inhibiting distractions, and processing visual information while carrying out motor functions (Cameron, 2018). Literacy and mathematics achievement interrelate as well and support later performance (Brock, Kim, & Grissmer, 2018). There appears to be a special role for mathematics as a foundation of both cognitive and academic skills (Aunola, Leskinen, Lerkkanen, & Nurmi, 2004).

Despite growing support for the idea that academic and cognitive skills co-develop at the transition to formal schooling, few studies from a co-development perspective incorporate EF, visuo-motor integration, applied problems, *and* early literacy knowledge. Furthermore, existing studies of cross-domain associations have primarily relied on cross-

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lagged panel models (Brock, Kim, and Grissmer, 2018; Fuhs et al., 2014; Kim et al., 2017). These models have been critiqued, however, for conflating between and within person effects (Berry & Willoughby, 2016). Prior studies have also mainly included children from a single location, which limits the generalizability of results.

To address these gaps, this study examined how the foundational cognitive skills of EF and visuo-motor integration, as well as children's academic skills in applied number problems and letter-word knowledge were associated with their kindergarten-year improvement in all four skills. We used data collected in two U. S. states, which increases the generalizability of results. We were particularly interested in which skills were associated with progress over the school year. We used two analytic approaches to examine (1) the contribution of children's school-entry cognitive, mathematics, and literacy skills to improvement across the other skills, and (2) whether improvement over the year in one of the four skills is associated with progress in the three other skills we measured. Addressing these two questions can help early childhood professionals know what to assess and what to emphasize, as they strive to better prepare entering kindergarteners for the demands of that increasingly rigorous and academically-focused environment (Bassok et al., 2016; Guarino, Dieterle, Bargagliotti, & Mason, 2013).

Co-development among cognitive and academic skills

School readiness skills do not develop in isolation but are interdependent and interrelated, starting early in life (McClelland & Cameron, 2018). Different cognitive systems underlie academic readiness, with origins in the non-academic domain of motor development. As the motor system develops, the theory of *learning to learn* (Adolph, 2008) describes how the coordination of reaching, grasping, and walking take place in a changing body to produce solutions to novel locomotor challenges. As an infant's physical body adapts to changing environmental demands, their motor and executive systems share overlapping neural networks and develop in concert (Diamond, 2000).

Whereas the motor system is not the only network linked to cognitive development, these connections demonstrate deep cross-domain associations among EF, motor skills, and early achievement (Becker, Miao, Duncan, & McClelland, 2014; Cameron et al., 2012). Specifically, empirical evidence shows that two cognitive skills in particular, EF and visuo-motor integration, are foundations for academic achievement in both literacy and mathematics (Cameron et al., 2012; Grissmer et al., 2010; McClelland et al., 2007; Welsh, Nix, Blair, Bierman, & Nelson, 2010). Moreover, gains in academics, especially mathematics, are associated with improving in both these cognitive skills (Schmitt, Purpura, Geldhof, Duncan, & McClelland, 2017; Clements, Sarama, & Germeroth, 2016; Espy et al., 2004; Fuhs et al., 2014).

Cognitive skills predict academic skills

EF refers to three distinct higher order cognitive processes involved in adaptive, goal-directed behavior: working memory, cognitive flexibility, and inhibitory control (Garon et al., 2008; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). *Visuo-motor integration* relies on the combination of fine motor skills and visual-spatial perceptual skills (Beery & Beery, 2006) and similar to EF, is comprised of several subprocesses: perceiving and understanding spatial orientation, synthesizing parts into a whole, constructing and manipulating representations, and reproducing models using controlled muscle movements (Carlson et al., 2013; Korkman, Kirk, & Kemp, 1998; Newcombe & Frick, 2010).

EF is at play in the classroom when children must stay on task and work independently, while avoiding distractions and inhibiting inappropriate responses. Visuo-motor integration supports children in parsing new, complex visual information and manipulating classroom materials and tools. Furthermore, associations between EF and visuo-motor integration and achievement arise at least in part because many complex cognitive tasks involved in reading and mathematics also rely on visual and spatial processing (Cameron, 2018; Son & Meisels, 2006). Academic tasks also require children to pay attention, to persist when tasks are challenging, to shift attention when rules change, and to hold and manipulate information in mind (Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). Children's initial levels, as well as improvements, in these two cognitive processes are robust predictors of their academic skills.

Evidence for initial cognitive skills predicting academic outcomes

Cross-sectional and longitudinal studies show that EF and its components, measured at a single time point, relate to both math and literacy achievement, after controlling for various explanatory factors like demographic information, child IQ, and prior achievement (Becker et al., 2014; Blair & Razza, 2007; Bull, Johnston, & Roy, 1999; Cragg, Keeble, Richardson, Roome, & Gilmore, 2017; Ribner, Willoughby, Blair, & The Family Life Project Key, 2017). Similarly, researchers have established a robust connection between children's initial level of visuo-motor integration and their concurrent and later achievement in literacy and mathematics outcomes (Carlson et al., 2013; Dehaene, Molko, Cohen, & Wilson, 2004; Geary, 2004; Grissmer et al., 2010). When measures of EF and visuo-motor integration are included at the same time, they are uniquely predictive of academic skills (Cameron et al., 2012; Carlson et al., 2013; Kim et al., 2017).

In addition, associations persist throughout the school years: for example, Cragg et al. (2017) reported that EF was associated with mathematics achievement between ages 8 and 25. Another study found that attention and persistence at age 4 predicted later math and reading and college completion (McClelland, Acock, Piccinin, Rhea, & Stallings, 2013). Davis, Pitchford, and Limback (2011) found in a cross-sectional sample of children ages 7 to 15 that visuo-motor integration and perceptual skills fully explained the links between motor skills and achievement at all ages. While these previous studies demonstrate how cognitive skills contribute to academic success, they primarily examine EF and visuo-motor integration separately in relation to academic skills, despite co-development of the skills. As such, examining cross-domain associations between EF, visuo-motor integration, and achievement can clarify and better specify interrelations among the processes at the transition to formal schooling.

Evidence for improvement in cognitive skills predicting academic outcomes

Not only initial levels, but *improving* in cognitive skills contributes to children's academic achievement. For example, four-year-olds who improved in a common measure of EF that requires children to self-regulate their gross motor behaviors, the Head-Toes-Knees-Shoulders (HTKS) task, also learned relatively more in applied problems, language, and letter-word skills from fall to spring (McClelland et al., 2007). This pattern was replicated in a different study using component measures of EF (Welsh et al., 2010). In addition, Li and Geary (2013) found that gains in visuospatial memory from first grade to fifth grade remained a significant predictor of children's mathematics achievement, but not reading, even after controlling for processing speed, intelligence, and in-class attention behavior. These studies are limited, however, because they did not examine whether improvements in academic skills including early literacy and mathematics *also* predicted gains in cognitive skills (Clements et al., 2016).

Scholars note that expanding one's academic skills also expands one's cognitive capacities (Blair & Raver, 2015; Clements et al., 2016). In line with this, Fuhs et al. (2014) showed that EF and achievement in mathematics and oral comprehension developed bi-directionally among 4-year-olds. Specifically, children who had high early levels of EF, mathematics, and oral comprehension developed better skills in the other domains measured. Another study using four time points between preschool and kindergarten found bi-directional relations between EF and mathematics over preschool, whereas by kindergarten, early EF predicted math gains, but early math did not predict EF gains (Schmitt, Purpura, et al., 2017).

Especially in early childhood, academic skills and cognitive skills are closely tied—and in the classroom, activities may support the development of academic skills, as well as the cognitive processes that underlie mathematics and literacy skills (Kim et al., 2017). Especially during kindergarten, academic tasks involve fine and visuo-motor skills (Marr, Cermak, Cohn, & Henderson, 2003) and manipulatives (Guarino et al., 2013). Such tasks provide children with opportunities to practice integrating multiple processes, thereby developing EF and visuo-motor integration skills while they learn academic content. Reflecting this, children's early levels of visuo-motor integration and attention as one component of EF each contributed to their mathematics achievement over two years—which in turn contributed to their visuo-motor integration and attention (Kim et al., 2017).

Increasing generalizability for findings of cognitive and academic skill co-development

In another similar study, longitudinal associations among EF, visuo-motor integration, applied problems, and letter word-ID were examined from kindergarten entry to the end of second grade (Brock, Kim, & Grissmer, 2018). Results showed differential patterns of associations between EF, visuo-motor integration, and academic skills over time. However, the Brock et al. study focused only on a low-income sample from a single U.S. city in the South, thereby making it difficult to discern whether findings are generalizable or particular to the study sample. In addition, Brock et al. (2018) conducted cross-lagged models, which accounts for temporal stability, but implicitly assumes that each participant varies over time around the same means. This underestimates the possibility of uncovering trait-like individual differences (Hamaker, Kuiper, & Grasman, 2015).

To address these issues and increase generalizability of findings of co-development, we replicate and extend prior work in a few notable ways. First, we use a multi-site study to replicate cross-lagged findings examining how earlier skills predict residual change in other skills, accounting for children nested within kindergarten classrooms. Second, we add time two skills to the prior model to examine how changes in skills predict residualized change in other skills. Finally, to adjust for factors that could have stable influences on skills between different children, we used a child fixed effects approach to examine associations among skills only using within-child variability, and draw conclusions based on both random- and fixed-effects results.

Research questions and hypotheses

We included a large sample of children from two U. S. States, and used multiple analytic approaches to address two primary questions of (1) whether *initial levels* in four cognitive and academic skills predict gains in other skills, and (2) whether *gains* in these skills predict gains in the other skills. For the first question, we use a traditional cross-lagged panel approach to replicate previously but mostly separately established associations among four cognitive and academic skills: EF, visuo-motor integration, applied number, and letter-word knowledge. Thus, we controlled for initial level when modeling a focal outcome, such as applied number skills, and assessed whether initial levels in the three other skills—in this example, EF, visuo-motor integration, and letter-word knowledge— predicted improvement in that outcome. Based on existing work with kindergarteners (Schmitt et al., 2017; Cameron et al., 2012), we expected cross-domain associations to emerge, especially among EF and applied problems, and between visuo-motor integration and letter-word knowledge.

For the second question, we use two analytic approaches. First, we add time 2 predictors to the prior cross-lag panel model to examine how gains in the predictors relate to each outcome (e.g., McClelland et al., 2007). Second, we use child fixed effects analyses to examine whether changes in particular skills predict changes in other skills (McClelland et al., 2014; Willoughby, Kupersmidt, & Voegler-Lee, 2012). Examining only within-child variability avoids bias that could inflate estimates due to assumed time-invariant factors (such as sex or SES) at the between-child level. On the basis of existing research (McClelland et al., 2007) and theory (Clements et al., 2016), we hypothesized that children who improved over time in cognitive skills (especially EF) would also improve in mathematics and literacy skills; and that children who improved in applied problems would improve in EF. Recent research also suggests that kindergarteners who improve in overall mathematics also learn more in visuo-motor integration (Kim et al., 2017). Therefore, we hypothesized that children who improved in applied problems would also make greater improvements in visuo-motor integration.

Method

This study combined data with the same measures collected at two time points from two sites in the U. S. (Oregon and South Carolina). We refer to the first assessment point for all children as Time 1 (T1) and the second assessment point as Time 2 (T2). In Oregon, T1 was the spring of participants' prekindergarten year and T2 was the spring of participants' kindergarten year. In South Carolina, T1 was the summer and fall of kindergarten entry, and T2 was the summer and fall of first grade. This means the Oregon sample was roughly three months younger than the South Carolina sample at T1 and T2. Importantly, both samples were tested on average one year apart, showed similar variability in age at each time point ($SD = 0.32$–0.35), and experienced roughly a year of kindergarten between T1 and T2. All models controlled for age and site.

Table 1
Descriptive statistics among study variables for children from two sites.

	Combined			Oregon			South Carolina		
	N	M (%)	SD	N	M (%)	SD	N	M (%)	SD
Male	555	(48.47%)		304	(50.66%)		251	(45.82%)	
Mom High School	493	(80.73%)		263	(87.45%)		230	(73.04%)	
Spanish-speaking	555	(7.74%)		304	(14.14%)		251	(0%)	
Age at Time 1 (years)	550	5.28	0.34	304	5.15	0.30	246	5.43	0.32
Age at Time 2 (years)	522	6.28	0.35	304	6.16	0.30	218	6.45	0.34
T1 HTKS	543	21.14	18.15	297	25.75	17.86	246	15.58	16.92
T2 HTKS	517	36.20	16.76	300	39.21	15.94	217	32.04	17.01
T1 VMI	545	13.26	2.46	300	13.48	2.58	245	12.99	2.29
T2 VMI	518	15.95	2.26	301	16.33	2.35	217	15.41	2.01
T1 LWI	545	353.53	26.26	300	351.33	26.98	245	356.23	25.16
T2 LWI	517	402.19	33.92	300	399.45	35.61	217	405.97	31.13
T1 AP	544	415.73	20.79	299	421.47	22.66	245	408.73	15.66
T2 AP	518	437.58	18.54	300	441.93	19.27	218	431.60	15.67

Note. HTKS = Head-Toes-Knees-Shoulders EF task; VMI = Beery-Buktenica Visuomotor Integration subtest; AP = WJ Applied problems; LWI = WJ Letter-word identification.

See Table 1 for descriptive statistics overall and by site.

Oregon (OR)

The Oregon site included 304 children (51% male) participating as part of a longitudinal correlational study of school readiness (see Schmitt et al., 2017 for more study-specific details). The sample of children in Oregon was diverse and reflected the demographic characteristics of the region with 51% of children attending Head Start. The sample was predominantly European-American (64%), but also included Latinx/Hispanic (17.8%) and multi-racial children (12.2%), with all other ethnicities representing just over 5% of the data. Children were recruited with letters sent home to parents, which included an incentive of $20 for participation at each wave of the study. For each wave of data collection, a trained research assistant tested children over 2–3 sessions, for 10–15 min each on a set of cognitive and academic assessments. Spanish-speaking children (14.14%) were identified by the child's teacher and assessed with Spanish versions of the measures by a Spanish-speaking research assistant. In their kindergarten year, children were in 116 classrooms in 33 schools.

South Carolina (SC)

Children ($N = 251$; 46% male) were recruited for a longitudinal evaluation of an after-school socio-emotional learning program in a low-income urban area of South Carolina. The study sample was socio-demographically representative of the community, with more than 90% African American residents and 90% living below the poverty line. Parents reported their ethnicity as follows: 84% African American, 8% Latino/Hispanic, 4% European-American/Other, and 5% unreported. Between April and September, any families with children entering kindergarten were recruited to participate in the study at one of four urban Title 1 elementary schools. Families completed a consent form and demographic questionnaire and were compensated with a $15 gift card. Consented children were individually assessed by trained research assistants during either a school-sponsored summer camp or early fall in a quiet location at the school. In their kindergarten year, children were in 45 classrooms in 4 schools.

Combined sample

The combined sample (see Table 1) included $N = 555$ children of average age 5.28 years at T1 and 6.28 at T2. The sample was 48% male; 80.7% of children's mothers finished high school, and 7.7% of children (OR only) were Spanish-speaking and assessed in Spanish. We examined site differences and controlled for site in all analyses; see "Site Comparison" section.

Measures

The measures we used for this study were the same at both sites.

Executive function

The Head-Toes-Knees-Shoulders (Cameron Ponitz, McClelland, Matthews, & Morrison, 2009; McClelland et al., 2014) task was used to measure EF. The HTKS requires children to behaviorally integrate three components of EF—inhibitory control, working memory, and attention-focusing and shifting—as they give gross motor responses. The HTKS comprises three parts, with each part increasing in complexity. First, children are instructed to touch their head when asked to "touch your toes" and touch their toes when asked to "touch your head." Then they must touch knees when told to touch shoulders; and finally, switch the rules for familiar commands such as touching their head when told to touch their knees. For each item, children are given a score of 0 (incorrect), 1 (self-correct), or 2 (correct). To advance to the next part, children must score four or more points. The HTKS has strong reliability, with alphas ranging from 0.92–0.94 (McClelland et al., 2014). Cronbach's alpha reliability was 0.96 at T1 and 0.95 at T2 in OR; and 0.97 at both T1 and T2 in SC.

Visuo-motor integration

Children's visuo-motor integration was measured using the Beery-Buktenica Developmental Test of Visual-Motor Integration (VMI; Beery & Beery, 2006), a normed assessment for 2 years through adulthood. The Beery VMI requires children to copy geometric figures that are increasingly complex, ranging from single lines forming 2-dimensional shapes to combined shapes that represent 3-dimensional objects. Cronbach's alpha reliability was 0.77 at T1 and 0.72 at T2 in OR; and 0.84 at T1 and 0.95 at T2 in SC.

Academic skills

Applied numeracy and letter-word knowledge were directly assessed using the Applied problems and Letter-word identification subtests, respectively, of the Woodcock-Johnson Tests of Achievement (WJ-III; Woodcock, McGrew, & Mather, 2001).

Applied problems

Applied problems requires children to analyze and solve mathematics problems that the researcher administers orally, directing children's attention to an accompanying flipbook. Children must view the problem representation while listening to the problem, recognize the procedure to follow, and then perform simple calculations. Furthermore, children must recognize which information is extraneous and which is important for solving the problem.

Emergent literacy

Letter-word identification measures children's letter and word identification skills by asking them to first identify lower- and uppercase letters, and then increasingly difficult words.

For both subtests, children are given a score of 0 (incorrect) or 1 (correct) on each item. The assessor stops when children answer six incorrect items in a row. Both subtests have strong published test-retest reliability ($r = 0.93–0.94$) and validity (Mather & Woodcock, 2001). Cronbach's alpha reliabilities for Applied problems were 0.81 (English-speakers) and 0.82 (Spanish-speakers) at T1 and 0.83 (English-speakers) and 0.80 (Spanish-speakers) at T2 in OR; and 0.84 at T1 and 0.93 at Time 2 in SC. Reliabilities for Letter-word identification were 0.92 (English-speakers) and 0.80 (Spanish-speakers) at T1 and 0.94 (English-speakers) and 0.90 (Spanish-speakers) at T2 in OR; and 0.91 at T1 and 0.96 at T2 in SC. W-scores were used in analyses.

Site comparison

The two sites did not statistically significantly differ at T1 on the proportion male. The two sites were significantly different on all other T1 variables: children in SC were older by roughly 3.5 months (or 0.28 of a year), $t(548) = 10.53, p < .001$, and performed roughly 5 W-score points better on letter-word identification, $t(543) = -2.18, p = .03$. In contrast, in OR, there were roughly 14% more mothers who reported earning at least a high school degree, $z = 4.05, p < .001$ and 14% more Spanish-speakers (i.e., there were none in SC), $z = 6.20, p < .001$; OR children performed about 10 points better on the HTKS, $t(541) = 6.77, p < .001$, about half a point better on the Beery VMI, $t(543) = 2.29, p = .02$, and 13 W-score points better on Applied problems, $t(542) = 7.46, p < .001$.

Differences may reflect overall socio-demographic advantages of children from OR. At the same time, differences did not all favor one site. Based on this, all models included socio-demographic covariates and full information maximum likelihood (FIML) to adjust for differences as well as a dummy variable for site. Additionally, we ran analyses for each site separately, which allowed every association to vary by site. Patterns for key predictors were similar across sites, and thus, we present the combined site results with the dummy variable adjusting for site differences. See Tables A1 and A2 for site-specific results for research questions one and two.

Analytic plan

All analyses were conducted using M*plus* 8 or Stata 15.1. Multi-level modeling in M*plus* was used with the kindergarten classroom cluster (70 classrooms with a mean of 8 children per classroom). ICCs were as follows: 0.05 for HTKS, 0.15 for VMI, 0.23 for Applied Problems, and 0.26 for Letter-Word Identification. Thus, it was important to account for the clustered nature of data. Additionally, M*plus* models used full information maximum likelihood, so all available data was used to inform model estimates. All M*plus* models included child age at T1, sex (female = 0; male = 1), maternal education (less than High School = 0; High School or more = 1), language status (English-speaking = 0; Spanish-speaking = 1), and site (OR = 0; SC = 1) as control variables. We included site in all models to adjust for any unobserved site-related characteristics that could influence outcomes but were not captured by other covariates.

Three sets of analyses are presented in the results section, one for research question 1 and two different sets of models for research question 2. First, a single M*plus* model was run that estimated the effects of T1 skills on residualized change for T2 skills (i.e., cognitive and academic outcomes). Therefore, the four T2 outcomes included were HTKS, Beery VMI, Applied problems, and Letter-word identification with all four skills as T1 predictors.

Second, to this initial model, we added in the T2 variables for available skills (i.e., for the T2 Applied problems outcome, T2 scores for HTKS EF, Beery VMI, and Letter-word identification were included). Due to convergence issues if attempting to run the four outcomes simultaneously (i.e., T2 HTKS is both a predictor and predicted by T2 Applied Problems), four random effects models were run separately by outcome and addressed associations between the co-development of skills during kindergarten.

Third, a more conservative approach for addressing research question 2 used child fixed effects analyses so only within child variability was examined. No time-invariant factors could be included as control variables because they were assumed not to vary within the individual (i.e., sex, maternal education, language status, and site). We initially included age and time point as control variables, but these variables were collinear making their effects difficult to interpret. Thus, we present the models with just age in them, though the models that include both age and time point variables are available upon request.

Results

Descriptive statistics for the combined sample and for each site are presented in Table 1. Of the 555 children in the study, 548 had at least one completed direct assessment at T1 ($n = 302$ for OR; $n = 246$ for SC) and 521 had at least one completed direct assessment at T2 ($n = 303$ for OR; $n = 218$ for SC). Children in SC and younger children at T1 were more likely to have left the study by T2. Such associations support using these control variables in the FIML models to provide less biased estimates than would list-wise deletion or an assumption of missing at random (Acock, 2012), but do not rule out whether unobserved variables produced bias in the estimates. Correlations between all covariates are shown in Table 2. Complete results for RQs 1 and 2 with statistical significance are presented in Tables 3 and 4 (RQ1) and Table 5 (RQ2).

RQ1. What are the associations between children's initial EF, visuo-motor integration, applied problems, and emergent literacy; and their kindergarten-year improvements in these skills?

For the outcome of Applied problems, children with higher initial HTKS ($\beta = 0.13$, $p < .001$), Beery VMI ($\beta = 0.08$, $p < .01$), and Letter-word identification ($\beta = 0.12$, $p < .01$) made significant improvement during the kindergarten year. Similarly, for the outcome of Letter-word identification, children with higher initial HTKS ($\beta = 0.09$, $p < .01$), Beery VMI ($\beta = 0.08$, $p < .05$), and Applied problems ($\beta = 0.19$, $p < .001$) scores made significant improvement. For the outcome of HTKS, only children with higher initial Applied problems ($\beta = 0.29$, $p < .001$) made significant improvement. For the outcome of Beery VMI, children with higher initial HTKS ($\beta = 0.11$, $p < .05$) and Applied problems ($\beta = 0.17$, $p < .01$) scores made significant improvement. See Table 3.

RQ2. What are associations among improvements in each of the four skills measured using random and fixed effects models?

In the random effects model, children who improved more in Applied problems during kindergarten made significantly more gains in all three skills: for HTKS EF, the coefficient for Applied problems was ($\beta = 0.31$, $p < .001$); for Beery VMI, it was $\beta = 0.15$, $p < .05$; and for Letter-word identification, the Applied problems coefficient was $\beta = 0.21$, $p < .001$. In addition, children who improved in each of the three skills also learned more in Applied problems during kindergarten: the coefficient for HTKS EF was $\beta = 0.20$, $p < .001$; for Beery VMI, $\beta = 0.11$, $p < .05$; and for Letter-word identification ($\beta = 0.20$, $p < .001$). Children who improved more in Beery VMI ($\beta = 0.10$, $p < .05$) during kindergarten gained significantly more in Letter-word identification. Likewise, improvement in Letter-word identification ($\beta = 0.13$, $p < .05$) during the kindergarten year was associated with significant gains in Beery VMI. Finally, although children with high initial HTKS scores made greater gains in Beery VMI and Letter-word identification for RQ1, change in HTKS did not predict gains in either of these outcomes for RQ2. See Table 4.

For the fixed effects analyses, which examines only those factors that vary over time within children, none of the time-invariant control variables in the prior models were included (e.g., sex, site). Results were largely consistent with the M*plus* models, particularly in that changes in Applied Problems predicted changes in the three other skills measured: the coefficient for Applied problems predicting HTKS EF was $\beta = 0.13$, $p < .01$; for Applied problems predicting Beery VMI was $\beta = 0.10$, $p < .05$; and for Applied problems predicting Letter-word identification, it was ($\beta = 0.11$, $p < .05$) (see Table 5). Likewise, changes in all other skills (i.e., HTKS EF, $\beta = 0.13$, $p < .01$; Beery VMI, $\beta = 0.10$, $p < .05$; and Letter-word identification, $\beta = 0.10$, $p < .05$) predicted changes in Applied Problems. Unlike prior models, we did not find significant effects for changes in Letter-Word Identification predicting Beery VMI, or vice versa.

Discussion

To our knowledge, this is the first study to examine the co-development of four school readiness skills (the two cognitive skills of EF and visuo-motor integration; and the two academic skills of applied problems and letter-word identification) in kindergarten-aged children, using diverse samples of 5-year-olds from two U.S. states, with multiple analytic approaches. Two main findings mapped to each research question. First, in terms of *starting place*, children who began school with higher levels of each of the four skills improved more in both academic skills, relative to children who started lower. Second, in terms of *change over the year*, children who improved more relative to other children in applied problems also had relatively greatly gains in both cognitive skills and letter-word identification. Similarly, children who improved in EF, visuo-motor integration, and letter-word identification also improved more in applied problems. Generally, this study provides robust evidence that cognitive and academic skills co-develop during kindergarten, with domain specificity between letter-word knowledge and visuo-motor skills, and an important role overall for applied problems.

Table 2
Correlations between study variables using the combined site sample.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
1. OR	–												
2. Male	0.05	–											
3. Mom Ed.	0.18***	0.01	–										
4. ELL	0.26***	0.07	−0.23***	–									
5. T1 Age	−0.41***	−0.01	−0.06	−0.03	–								
6. T2 Age	−0.41***	−0.01	−0.06	−0.03	0.95***	–							
7. T1 HTKS	0.28***	−0.06	0.20***	−0.14**	0.01	−0.02	–						
8. T2 HTKS	0.21***	−0.09*	0.21***	−0.16***	0.01	0.02	0.53***	–					
9. T1 VMI	0.10*	−0.02	0.11*	−0.06	0.14**	0.10*	0.31***	0.32***	–				
10. T2 VMI	0.20***	−0.14**	0.16***	−0.07	−0.02	−0.04	0.38***	0.34***	0.58***	–			
11. T1 LWI	−0.09*	−0.04	0.10*	−0.21***	0.14**	0.11*	0.32***	0.31***	0.41***	0.33***	–		
12. T2 LWI	−0.09*	−0.05	0.14**	−0.17***	0.15***	0.15***	0.34***	0.37***	0.40***	0.39***	0.70***	–	
13. T1 AP	0.31***	−0.02	0.23***	−0.30***	0.09*	0.07	0.59***	0.53***	0.48***	0.48***	0.47***	0.48***	–
14. T2 AP	0.28***	0.02	0.24***	−0.24***	0.04	0.06	0.53***	0.58***	0.45***	0.48***	0.46***	0.52***	0.75***

Note. OR is if the site was Oregon. Mom Ed. is if the child's mother reported having at least a High School degree. ELL is yes if the child speaks primarily Spanish. HTKS is the Head-Toes-Knees-Shoulders EF task; VMI = Beery-Buktenica Visuomotor Integration subtest. AP = WJ Applied problems; LWI = WJ Letter-word identification.

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

A strong start: early academic achievement has many foundations

What do we mean by a strong start? That children enter kindergarten with skills already in place—either from developmental or educational influences (Burrage et al., 2008). Strong entry skills means children can draw on these advantages early in the school transition, when they are adjusting to the classroom and the heightened expectations in kindergarten as opposed to preschool. One important pattern from looking at the role of kindergarten-entry skills is that *all* skills we assessed—two cognitive as well as two academic skills—were associated with improving in the two academic skills of letter-word identification and applied problems. Thus, we conclude that early achievement has many foundations, for example:

- EF: Children who begin kindergarten with good EF are at a distinct advantage because learning early literacy and numeracy requires inhibitory control to stay on task, working memory to track and update new information, and cognitive flexibility to shift one's attention when needed.
- Visuo-motor integration: Children who begin kindergarten able to use a writing utensil to copy the symbols that they see are advantaged given the many perceptual and motor processes involved in learning to read and in learning to perform quantitative tasks including counting, comparisons including those with manipulatives, and simple calculations.
- Applied problems skills: Children who begin kindergarten able to count, perform simple addition and subtraction, recognize and assign value in problems of time-telling and money, and to assess magnitude are advantaged in symbol recognition, which is involved in learning literacy as well as mathematics.
- Letter-word knowledge: Children who begin school able to recognize letters in lower- and upper-case are advantaged because of the heavy focus in kindergarten on learning to read, and because of the involvement of symbols in complex measures of mathematics skills, of which applied problems is one.

Early in the school trajectory, mathematics and literacy tasks share the demands of symbolic representation and recognition. They also share the cognitive process of switching between part and whole. For example, children need to visualize part-whole relationships to solve addition problems; similarly, they need to identify the individual letters that make up whole words. Finally, children who can more readily recognize letters and words may have greater prior exposure to other academic tasks including quantitative problems.

Table 3
Bidirectional associations between EF, VMI, applied problems, and letter-word identification (N = 555).

	Cognitive Skills						Academic Skills					
	HTKS			VMI			AP			LWI		
	B	(SE)	β	B	(SE)	β	B	(SE)	β	B	(SE)	β
Mom Edu	3.02	(2.30)	0.07	0.18	(0.22)	0.03	2.25	(1.32)	0.05	3.90	(2.54)	0.05
Male	−2.11	(1.19)	−0.06	−0.51	(0.18)	−0.11	1.49	(1.15)	0.04	−1.23	(2.06)	−0.02
ELL	0.12	(4.84)	0.00	0.27	(0.29)	0.03	−2.79	(2.35)	−0.04	9.96	(5.49)	0.08
SC	−0.58	(1.53)	−0.02	−0.13	(0.23)	−0.03	−2.80	(1.79)	−0.08	12.57	(2.88)	0.19***
T1 Age	−0.90	(1.75)	−0.02	−0.57	(0.24)	−0.09*	0.20	(1.46)	0.00	−1.38	(3.44)	−0.01
T1 Math	0.23	(0.06)	0.29***	0.02	(0.01)	0.17**	0.47	(0.04)	0.53***	0.31	(0.07)	0.19***
T1 LWI	0.02	(0.03)	0.04	0.00	(0.00)	0.04	0.08	(0.03)	0.12**	0.70	(0.07)	0.55***
T1 HTKS	0.28	(0.04)	0.31***	0.01	(0.01)	0.11*	0.13	(0.03)	0.13***	0.16	(0.06)	0.09**
T1 VMI	0.38	(0.42)	0.06	0.41	(0.04)	0.45***	0.61	(0.23)	0.08**	1.08	(0.55)	0.08*

Note. ELL (0 = no; 1 = yes) is yes if the child speaks primarily Spanish. HTKS is the Head-Toes-Knees-Shoulders EF task; VMI = Beery-Buktenica Visuomotor Integration subtest. AP = WJ Applied problems; LWI = WJ Letter-word identification.

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

Table 4
Associations between Improvements in EF, VMI, applied problems, and letter-word identification ($N = 555$).

	Cognitive Skills						Academic Skills					
	HTKS			VMI			AP			LWI		
	B	(SE)	β	B	(SE)	β	B	(SE)	β	B	(SE)	β
Mom Edu	1.93	(2.16)	0.05	0.17	(0.21)	0.03	1.10	(1.11)	0.03	2.69	(2.59)	0.03
Male	−2.55	(1.23)	−0.08*	−0.53	(0.18)	−0.13**	2.48	(1.24)	0.08*	−0.83	(2.07)	−0.01
ELL	0.34	(4.37)	0.01	0.25	(0.27)	0.03	−4.33	(1.54)	−0.07**	10.46	(5.04)	0.09*
SC	−0.38	(1.31)	−0.01	−0.19	(0.22)	−0.05	−3.99	(1.55)	−0.13*	13.87	(2.70)	0.22***
T1 Age	−0.87	(1.74)	−0.02	−0.55	(0.23)	−0.09*	1.10	(1.40)	0.02	−0.46	(3.40)	−0.01
T1 Math	0.08	(0.05)	0.11	0.01	0.01	0.07	0.37	(0.04)	0.49***	0.06	(0.09)	0.04
T1 LWI	−0.03	(0.03)	−0.04	−0.00	0.01	−0.05	0.00	(0.03)	0.00	0.66	(0.07)	0.56***
T1 HTKS	0.24	(0.04)	0.29***	0.01	0.01	0.09	0.04	(0.03)	0.05	0.06	(0.06)	0.03
T1 VMI	0.17	(0.41)	0.03	0.39	0.04	0.46***	0.10	(0.20)	0.02	0.20	(0.60)	0.02
T2 Math	0.30	(0.05)	0.31***	0.02	0.01	0.15*				0.41	(0.10)	0.21***
T2 LWI	0.04	(0.03)	0.08	0.01	0.00	0.13*	0.10	(0.03)	0.20***			
T2 HTKS				−0.00	0.01	−0.01	0.22	(0.04)	0.20***	0.11	(0.07)	0.06
T2 VMI	−0.11	(0.27)	−0.01				0.10	(0.03)	0.11*	1.45	(0.69)	0.10*

Note. ELL (0 = no; 1 = yes) is yes if the child speaks primarily Spanish. HTKS is the Head-Toes-Knees-Shoulders EF task; VMI = Beery-Buktenica Visuomotor Integration subtest. AP = WJ Applied problems; LWI = WJ Letter-word identification.

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

Evidence for co-development

Co-development means that improvements travel together. In other words, improving in one skill domain happens simultaneously with improvements in a different domain. In terms of school readiness, co-development means that even if children enter kindergarten with minimal skills, they can thrive as long as they successfully learn over the year. We found evidence for co-development of applied problems and all other skills, suggesting that when children gain applied quantitative competencies, they are also likely to learn more in literacy and make cognitive gains in EF as well as visuo-motor processes (McClelland & Cameron, 2018). When children learn mathematics, they exercise the same processes, like working memory, that underlie improvement in EF; preliminary evidence suggests that by the end of kindergarten, the HTKS measure of EF draws heavily on working memory (McClelland et al., 2014). The associations we found could also arise from the generalized nature of the WJ applied problems assessment, which involves real-world knowledge such as the value of different coins and how to tell time, as well as vocabulary skills, familiarity with animals pictured in the problems, and the need to ignore distractors, which draws on EF.

Other evidence for co-development emerged between visuo-motor integration and letter-word identification. Whereas children's initial levels of letter-word identification did not matter for their visuo-motor integration improvement, improving in each was associated with greater reciprocal improvement. In other words, visuo-motor integration and letter-word identification may develop together, and a child's starting place in literacy appears not to matter nearly as much as whether children are able to improve when they enter the classroom. Intense emphasis on direct literacy instruction in today's typical kindergarten (Bassok et al., 2016) means that children are likely given lots of opportunities to learn literacy. And with exposure to literacy-related tasks that require integrating alphabetic forms with their meaning, both letter-word and visuo-motor skills are exercised. The visuo-motor tasks prominent in kindergarten often have literacy components. For example, Marr et al. (2003) observed that kindergarteners spend almost half their day (46%) in fine motor activities, with 42% of those paper-pencil activities, including tasks like writing. Visuo-motor integration is closely aligned with early decoding skills in this age group (Ho, 2011), and our results corroborate this pattern.

Comparing fixed versus random effects results

Another contribution of this study was in our analytic approach, which combined data from two different sites. We also applied a random effects model along with a fixed effects model (McClelland

Table 5
Associations between changes in EF, VMI, applied problems, and letter-word identification ($N = 1047$).

	Cognitive skills						Academic skills					
	HTKS			VMI			AP			LWI		
	B	(SE)	β	B	(SE)	β	B	(SE)	β	B	(SE)	β
Age	12.23	(2.06)	0.08***	2.26	(0.25)	0.11***	15.14	(1.66)	0.11***	43.09	(2.48)	0.19***
AP	0.16	(0.05)	0.13**	0.01	(0.01)	0.10*				0.18	(0.08)	0.11*
LWI	0.01	(0.03)	0.01	0.00	(0.00)	0.05	0.06	(0.03)	0.10*			
HTKS				−0.01	(0.01)	−0.06	0.11	(0.04)	0.13**	0.02	(0.07)	0.01
VMI	−0.46	(0.35)	−0.06				0.64	(0.29)	0.10*	0.59	(0.52)	0.05

Note. ELL (0 = no; 1 = yes) is yes if the child speaks primarily Spanish. HTKS is the Head-Toes-Knees-Shoulders EF task; VMI = Beery-Buktenica Visuomotor Integration subtest. AP = WJ Applied problems; LWI = WJ Letter-word identification.

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

et al., 2014). The former is appropriate for understanding what factors explain changes between and within children, whereas the latter examines only what skills matter when it comes to changes within a child. Random effects models allow us to model nesting effects from children being clustered in different kindergarten classrooms, but these models may over-estimate the role of a given predictor because these predictors are often correlated with time-invariant factors (that may not be completely controlled for). In contrast, fixed effects models entirely adjust for non-changing child factors (such as classroom membership) and so are dependent on correctly modeling the time-variant factors that influence skill development.

Using both random and fixed effects approaches reveals those patterns that emerge consistently. In the present study, the primary fixed effects result was that applied problems skills co-develop with both cognitive skills of EF and visuo-motor integration, as well as the alternate achievement area of letter-word knowledge. Importantly, results suggest that the links between mathematics gains and these three other skills are not simply a function of between-person differences, but that changes within children also predict changes in other domains. This message is an important one to consider, given that literacy, more than applied problems, is the usual focus in kindergarten.

Experts argue that early childhood mathematics activities have potentially beneficial transfer effects for children's cognitive and linguistic development (Clements et al., 2016; Sarama, Lange, Clements, & Wolfe, 2012). Our study supports this idea, suggesting that children who deepen their understanding of quantitative concepts, symbols, and operations during the kindergarten year are able to make cognitive as well as literacy advances. This advantage could arise because certain applied problems understandings may help children perform other tasks; for example, a child who can count to twenty realizes that a complex design involves 9 dots arranged in a square-like grid, and this helps them plan their version of the design. Alternately, the same cognitive processes invoked by the applied problems measure are needed for other tasks; for example, working memory (which this study did not directly measure) is needed to compare and manipulate quantities, and is also part of EF, visuo-motor integration tasks, and word-decoding.

Limitations

This study's limitations have to do with design, measurement, and site considerations. The correlational design means we cannot infer causality, though the fixed effects approach means that results are not being driven by stable between-child factors. In addition, our reliance on only two time points prevents us from interpreting gains as growth, even though early in the elementary school trajectory is when children exhibit the most rapid growth in both mathematics and literacy (Cameron, Grimm, Steele, Castro-Schilo, & Grissmer, 2015). Having more time points would enable us to be more precise in understanding the reciprocal development of cognitive skills with achievement (Brock, Kim, et al., 2018). In addition, we had only single measures of each construct. The HTKS is a robust measure of EF and predicts achievement at least as well as other component measures (McClelland et al., 2014), but a working memory measure would add specificity. Similarly, visuo-motor integration is the aspect of fine motor skills most strongly linked to achievement (Cameron et al., 2012; Carlson et al., 2013; Davis et al., 2011) and the Beery VMI is arguably the most respected measure of this construct. Still, mathematics is a complex construct with some measures emphasizing number-specific and other measures emphasizing more general cognitive processes (Fuchs et al., 2010). As we noted, the Applied problems subtest is considered quite general, involving not just numerical skills but also vocabulary and EF processes. More comprehensive measurement, especially of mathematics, would increase the specificity with which we are able to describe foundational cognitive skills and achievement pathways, which research suggests are domain-specific (Cameron, Brock, et al., 2015; Kim & Cameron, 2016; Purpura, Schmitt, & Ganley, 2017). We did observe some site differences that we controlled for with covariates; yet the sample included children of similar ages at each site and separate analyses revealed similar patterns across sites. As noted previously, involving children from two distinct sites increases generalizability.

Implications for research and practice

Taken together, the fixed and random effects results are clear: *children's cognitive and academic skills develop together*, with applied number skills being intertwined with cognitive (e.g., EF and visuo-motor integration) and emergent literacy skills during kindergarten. When examining how skill improvements are associated across multiple domains, determining directionality is not possible, even with a fixed effects model, however. So our findings support the importance of cognitive skills as foundations of academic skills, even though it is academic activities that are increasingly emphasized in kindergarten settings (Bassok et al., 2016).

Our results suggest that all the skills we measured should be promoted in early childhood settings. On the one hand, we know that high quality early childhood environments have a strong emphasis on early literacy skills with an increasing emphasis on early mathematics (Weiland & Yoshikawa, 2013). Given our results for applied problems, engaging in early quantitative activities is likely beneficial for children's development in both cognitive and academic areas. On the other hand, children's developing cognitive skills like EF help determine whether they can effectively engage in, and learn from, available quantitative activities. EF by definition means that children can effectively attend to learning activities, and improving children's EF is associated with improvements in EF and academic outcomes (Pandey et al., 2018; Schmitt, McClelland, Tominey, & Acock, 2015). In addition, visuo-motor integration is a spatial skill that requires children to represent quantities, perform transformations, and rotate shapes (Cameron, 2018). These processes are closely tied to the development of numerical representations and math performance, and are implicated in many quantitative tasks (Verdine, Golinkoff, Hirsh-Pasek, & Newcombe, 2017). A focus on visuo-motor integration may also mean that children become more comfortable with using manipulatives (Brock, Murrah, Cottone, Mashburn, & Grissmer, 2018), an instructional approach which is tied to mathematics performance in kindergarten in the U. S. (Guarino et al., 2013).

Given our results and others', early childhood quantitative activities may serve children in multiple areas (Sarama et al., 2012). But skill drill and memorization of math facts are not developmentally appropriate, and didactic instructional approaches are actually associated with lower mathematics achievement in diverse samples (Stipek, Feiler, Daniels, & Milburn, 1995). Instead, our findings help reiterate that there is more to children's early academic competencies than initial measures of letters and numbers. That children who improved more in EF, visuo-motor integration, *and* letter-word knowledge also improved more in applied problems suggests that activities that exercise multiple skills and academic areas simultaneously may be best. One promising after-school curriculum that targeted visuo-motor integration with arts and crafts activities improved low-income kindergarteners' EF and spatial skills (Brock, Murrah, et al., 2018), with preliminary improvements for first graders' mathematics skills.

Conclusion

Our primary conclusion, that children need many skills to succeed in formal schooling, is not new. Yet both research and practice have tended to focus on academic achievement or pit one skill against another. Our study illuminates two skills—namely EF and visuo-motor integration—that are developing alongside number and letter-word skills. Shared processes among foundational cognitive skills and traditional academic skills, see for example (Cameron, 2018) help explain our pattern of findings where both initial level and gains matter, depending on the skill assessed. Remaining questions include what instructional activities would maximize learning in *all* these areas. Figuring this out is especially critical for our most vulnerable children. Skill drilling approaches are popular and may support literacy; however, research does not support their effectiveness for mathematics, and there are corresponding costs for student motivation (Stipek et al., 1995). Perhaps our findings can be used to inform the implementation of hands-on activities that are both developmentally appropriate, and that foster learning in both cognitive and academic skill areas.

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Appendix A. Appendix

Table A1
Site comparison effects for the initial-level analyses (research question 1).

	HTKS			VMI			Applied problems			Letter-word ID		
	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β
T1 Math	0.29***	0.29**	0.28***	0.17**	0.17*	0.14	0.53***	0.59***	0.39***	0.19***	0.20**	0.14**
T1 LWI	0.04	0.02	0.03	0.04	0.06	0.03	0.12**	0.15***	0.05	0.55***	0.58***	0.47***
T1 HTKS	0.31***	0.34***	0.26***	0.11**	0.11	0.12**	0.13***	0.08**	0.21**	0.09**	0.05	0.13*
T1 VMI	0.06	0.01	0.14	0.45***	0.47***	0.41***	0.08**	0.06	0.18**	0.08*	0.06	0.15**

Note. Maternal education, male, ELL, site, and age included as controls, but not shown.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table A2
Site comparison effects for the change score analyses (research question 2).

	HTKS			VMI			Applied problems			Letter-word ID		
	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β	Full Sample β	OR β	SC β
T1 Math	0.11	0.07	0.17***	0.07	0.10	0.02	0.49***	0.56***	0.32***	0.04	0.09	−0.01
T1 LWI	−0.04	−0.06	−0.06	−0.05	−0.03	−0.07	0.00	0.08	−0.12	0.56***	0.60***	0.52***
T1 HTKS	0.29***	0.34***	0.20***	0.09	0.12	0.05	0.05	−0.01	0.13*	0.03	0.03	0.04
T1 VMI	0.03	0.01	0.05	0.46***	0.49***	0.38***	0.02	0.02	0.05	0.02	0.01	0.06
T2 Math	0.31***	0.37***	0.23***	0.15*	0.12	0.18*				0.21***	0.15*	0.28***
T2 LWI	0.08	0.04	0.15	0.13*	0.11	0.16*	0.20***	0.13*	0.31***			
T2 HTKS				−0.01	−0.05	0.04	0.20***	0.23***	0.18***	0.06	0.03	0.10
T2 VMI	−0.01	−0.05	0.04				0.11*	0.08	0.15*	0.10*	0.09	0.12*

Note. Mom education, male, ELL, site, and age included as controls, but not shown.
* $p < .05$.
*** $p < .001$.

References

Acock, A. C. (2012). What to do about missing values. In H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf, & K. J. Sher (Eds.). *APA handbook of research methods in psychology, Vol 3: Data analysis and research publication* (pp. 27–50). Washington, DC, US: American Psychological Association.

Adolph, K. E. (2008). Learning to move. *Current Directions in Psychological Science, 17*(3), 213–218. https://doi.org/10.1111/j.1467-8721.2008.00577.x.

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

Bassok, D., Latham, S., & Rorem, A. (2016). Is kindergarten the new first grade? *AERA Open, 2*(1), https://doi.org/10.1177/2332858415616358.

Becker, D. R., Miao, A., Duncan, R., & McClelland, M. M. (2014). Behavioral self-regulation and executive function both predict visuomotor skills and early academic achievement. *Early Childhood Research Quarterly, 29*(4), 411–424. https://doi.org/10.1016/j.ecresq.2014.04.014.

Beery, K. E., & Beery, N. A. (2006). *Beery VMI administration, scoring, and teaching manual* (5th edition). Minneapolis, MN, USA: Pearson.

Berry, D., & Willoughby, M. T. (2016). On the practical interpretability of cross-lagged panel models: Rethinking a developmental workhorse. *Child Development.* https://doi.org/10.1111/cdev.12660.

Blair, C., Protzko, J., & Ursache, A. (2011). Self-regulation and early literacy. In S. B. Neuman, & D. K. Dickinson (Vol. Eds.), *Handbook of early literacy research. Vol. 3. Handbook of early literacy research* (pp. 20–35). New York, NY, USA: Guilford.

Blair, C., & Raver, C. C. (2015). School readiness and self-regulation: A developmental psychobiological approach. *Annual Review of Psychology, 3*(66), 711–731. https://doi.org/10.1146/annurev-psych-010814-015221.

Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647–663. https://doi.org/10.1111/j.1467-8624.2007.01019.x.

Brock, L. L., Kim, H., & Grissmer, D. W. (2018). Longitudinal associations among executive function, visuomotor integration, and achievement in a high-risk sample. *Mind, Brain, and Education, 12*(1), 23–27. https://doi.org/10.1111/mbe.12164.

Brock, L. L., Murrah, W. M., Cottone, E. A., Mashburn, A. J., & Grissmer, D. W. (2018). An after-school intervention targeting executive function and visuospatial skills also improves classroom behavior. *International Journal of Behavioral Development, 42*(5), 474–484. https://doi.org/10.1177/0165025417738057.

Bull, R., Johnston, R. S., & Roy, J. A. (1999). Exploring the roles of the visual-spatial sketch pad and central executive in children's arithmetical skills: Views from cognition and developmental neuropsychology. *Developmental Neuropsychology, 15*(3), 421–442. https://doi.org/10.1080/87565649909540759.

Burrage, M. S., Cameron Ponitz, C., McCready, E. A., Shah, P., Sims, B. C., Jewkes, A. M., & Morrison, F. J. (2008). Age- and schooling-related effects on executive functions in young children: A natural experiment. *Child Neuropsychology, 14*, 510–524. https://doi.org/10.1080/09297040701756917.

Cameron, C. E. (2018). *Hands on, minds on: How executive function, motor, and spatial skills* *foster school readiness.* New York City, NY: Teachers College Press.

Cameron, C. E., Brock, L. L., Hatfield, B. H., Cottone, E. A., Rubinstein, E., LoCasale-Crouch, J., & Grissmer, D. W. (2015). Visuomotor integration and inhibitory control compensate for each other in school readiness. *Developmental Psychology, 51*(11), 1529–1543. https://doi.org/10.1037/a0039740.

Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D. W., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development, 83*(4), 1229–1244. https://doi.org/10.1111/j.1467-8624.2012.01768.x.

Cameron, C. E., Grimm, K. J., Steele, J. S., Castro-Schilo, L., & Grissmer, D. W. (2015). Nonlinear Gompertz curve models of achievement gaps in mathematics and reading. *Journal of Educational Psychology, 107*(3), 789–804. https://doi.org/10.1037/edu0000009.

Cameron Ponitz, C. E., McClelland, M. M., Matthews, J. S., & Morrison, F. J. (2009). A structured observation of behavioral self-regulation and its contribution to kindergarten outcomes. *Developmental Psychology, 45*(3), 605–619. https://doi.org/10.1037/a0015365.

Carlson, A. G., Rowe, E., & Curby, T. R. (2013). Disentangling fine motor skills' relations to academic achievement: The relative contributions of visual-spatial integration and visual-motor coordination. *Journal of Genetic Psychology, 174*(5–6), 514–533. https://doi.org/10.1080/00221325.2012.717122.

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

Cragg, L., Keeble, S., Richardson, S., Roome, H. E., & Gilmore, C. (2017). Direct and indirect influences of executive functions on mathematics achievement. *Cognition, 162*, 12–26. https://doi.org/10.1016/j.cognition.2017.01.014.

Davis, E. E., Pitchford, N. J., & Limback, E. (2011). The interrelation between cognitive and motor development in typically developing children aged 4–11 years is underpinned by visual processing and fine manual control. *British Journal of Psychology, 102*(3), 569–584. https://doi.org/10.1111/j.2044-8295.2011.02018.x.

Decker, S. L., Englund, J. A., Carboni, J. A., & Brooks, J. H. (2011). Cognitive and developmental influences in visual-motor integration skills in young children. *Psychological Assessment, 23*(4), 1010–1016. https://doi.org/10.1037/a0024079.

Dehaene, S., Molko, N., Cohen, L., & Wilson, A. J. (2004). Arithmetic and the brain. *Current Opinion in Neurobiology, 14*(2), 218–224. https://doi.org/10.1016/j.conb.2004.03.008.

Diamond, A. (2000). Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. *Child Development, 71*(1), 44–56. https://doi.org/10.1111/1467-8624.00117.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., ... Japel, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428.

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

Fuchs, L. S., Geary, D. C., Compton, D. L., Fuchs, D., Hamlett, C. L., Seethaler, P. M., ... Schatschneider, C. (2010). Do different types of school mathematics development depend on different constellations of numerical versus general cognitive abilities? *Developmental Psychology, 46*(6), 1731–1746. https://doi.org/10.1037/a0020662.

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

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin, 134*(1), 31–60. https://doi.org/10.1037/0033-2909.134.1.31.

Geary, D. C. (2004). Mathematics and learning disabilities. *Journal of Learning Disabilities, 37*(1), 4–15. https://doi.org/10.1177/00222194040370010201.

Grissmer, D. W., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology, 46*(5), 1008–1017. https://doi.org/10.1037/a0020104 341037/a0020104.supp (Supplemental).

Guarino, C., Dieterle, S. G., Bargagliotti, A. E., & Mason, W. M. (2013). What can we learn about effective early mathematics teaching? A framework for estimating causal effects using longitudinal survey data. *Journal of Research on Educational Effectiveness, 6*(2), 164–198. https://doi.org/10.1080/19345747.2012.706695.

Hamaker, E. L., Kuiper, R. M., & Grasman, R. P. (2015). A critique of the cross-lagged panel model. *Psychological Methods, 20*(1), 102–116. https://doi.org/10.1037/a0038889.

Ho, C. A. (2011). Major developmental characteristics of children's name writing and relationships with fine motor skills and emergent literacy skills. *Unpublished doctoral dissertation*University of Michigan. Retrieved from https://deepblue.lib.umich.edu/handle/2027.42/84436.

Kim, H., & Cameron, C. E. (2016). Implications of visuospatial skills and executive functions for learning mathematics: Evidence from children with Autism and Williams Syndrome. *AERA Open, 2*(4), 2332858416675124. https://doi.org/10.1177/2332858416675124.

Kim, H., Duran, C. A., Cameron, C. E., & Grissmer, D. W. (2017). Developmental relations among motor and cognitive processes and mathematics skills. *Child Development*. https://doi.org/10.1111/cdev.12752.

Korkman, M., Kirk, U., & Kemp, S. (1998). *NEPSY: A Developmental Neuropsychological Assessment.* San Antonio, TX: The Psychological Corporation.

Li, Y., & Geary, D. C. (2013). Developmental gains in visuospatial memory predict gains in mathematics achievement. *PLoS One, 8*(7), e70160. https://doi.org/10.1371/journal.pone.0070160.

Marr, D., Cermak, S., Cohn, E. S., & Henderson, A. (2003). Fine motor activities in head start and kindergarten classrooms. *American Journal of Occupational Therapy, 57*(5), 550–557. https://doi.org/10.5014/ajot.57.5.550.

Mather, N., & Woodcock, R. W. (2001). *Examiner's manual Woodcock-Johnson III tests of achievement.* Itasca, IL: Riverside.

McClelland, M. M., Acock, A. C., Piccinin, A., Rhea, S. A., & Stallings, M. C. (2013). Relations between preschool attention span-persistence and age 25 educational outcomes. *Early Childhood Research Quarterly, 28*(2), 314–324. https://doi.org/10.1016/j.ecresq.2012.07.008.

McClelland, M. M., & Cameron, C. E. (2018). Developing together: The role of executive function and motor skills in children's early academic lives. *Early Childhood Research Quarterly*. https://doi.org/10.1016/j.ecresq.2018.03.014.

McClelland, M. M., Cameron, C. E., Connor, C. M., Farris, C. L., Jewkes, A. M., & Morrison, F. J. (2007). Links between behavioral regulation and preschoolers' literacy, vocabulary, and math skills. *Developmental Psychology, 43*(4), 947–959. https://doi.org/10.1037/0012-1649.43.4.947.

McClelland, M. M., Cameron, C. E., Duncan, R., Bowles, R. P., Acock, A. C., Miao, A., & Pratt, M. E. (2014). Predictors of early growth in academic achievement: The Head-Toes-Knees-Shoulders task. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00599.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734.

Newcombe, N. S., & Frick, A. (2010). Early education for spatial intelligence: Why, what, and how. *Mind, Brain, & Education, 4*(3), 102–111. https://doi.org/10.1111/j.1751-228X.2010.01089.x.

Pandey, A., Hale, D., Das, S., Goddings, A., Blakemore, S., & Viner, R. M. (2018). Effectiveness of universal self-regulation–based interventions in children and adolescents: A systematic review and meta-analysis. *JAMA Pediatrics, 172*(6), 566–575. https://doi.org/10.1001/jamapediatrics.2018.0232.

Purpura, D. J., Schmitt, S. A., & Ganley, C. M. (2017). Foundations of mathematics and literacy: The role of executive functioning components. *Journal of Experimental Child Psychology, 153*, 15–34. https://doi.org/10.1016/j.jecp.2016.08.010.

Ribner, A. D., Willoughby, M. T., Blair, C., & The Family Life Project Key, I (2017). Executive function buffers the association between early math and later academic skills. *Frontiers in Psychology,* 8. https://doi.org/10.3389/fpsyg.2017.00869.

Roebers, C. M., & Jäger, K. (2014). The relative importance of fine motor skills, intelligence, and executive functions for first graders' reading and spelling skills. *Perspectives on Language, Spring* (online edition).

Sarama, J., Lange, A. A., Clements, D. H., & Wolfe, C. B. (2012). The impacts of an early mathematics curriculum on oral language and literacy. *Early Childhood Research Quarterly, 27*(3), 489–502. https://doi.org/10.1016/j.ecresq.2011.12.002.

Schmitt, S. A., Geldhof, G. J., Purpura, D. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology*. https://doi.org/10.1037/edu0000193.

Schmitt, S. A., McClelland, M. M., Tominey, S. L., & Acock, A. C. (2015). Strengthening school readiness for head start children: Evaluation of a self-regulation intervention. *Early Childhood Research Quarterly, 30*(*Part A*(0), 20–31. https://doi.org/10.1016/j.ecresq.2014.08.001.

Schmitt, S. A., Purpura, D. J., Geldhof, G. J., Duncan, R., & McClelland, M. M. (2017). Examining the relations between executive function, math, and literacy during the transition to kindergarten: A multi-analytic approach. *Journal of Educational Psychology, 109*(8), 1120–1140. https://doi.org/10.1037/edu0000193.

Son, S.-H., & Meisels, S. J. (2006). The relationship of young children's motor skills to later reading and math achievement. *Merrill-Palmer Quarterly, 52*(4), 755–778. https://doi.org/10.1353/mpq.2006.0033.

Stipek, D. J., Feiler, R., Daniels, D., & Milburn, S. (1995). Effects of different instructional approaches on young children's achievement and motivation. *Child Development, 66*(1), 209–223. https://doi.org/10.2307/1131201.

Verdine, B. N., Golinkoff, R. M., Hirsh-Pasek, K., & Newcombe, N. S. (2017). I. Spatial skills, their development, and their links to mathematics. *Monographs of the Society for Research in Child Development, 82*(1), 7–30. https://doi.org/10.1111/mono.12280.

Verdine, B. N., Irwin, C. M., Golinkoff, R. M., & Hirsh-Pasek, K. (2014). Contributions of executive function and spatial skills to preschool mathematics achievement. *Journal of Experimental Child Psychology, 126*, 37–51. https://doi.org/10.1016/j.jecp.2014.02.012.

Weiland, C., & Yoshikawa, H. (2013). Impacts of a prekindergarten program on children's mathematics, language, literacy, executive function, and emotional skills. *Child Development, 84*(6), 2112–2130. https://doi.org/10.1111/cdev.12099.

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

Willoughby, M. T., Kupersmidt, J. B., & Voegler-Lee, M. E. (2012). Is preschool executive function causally related to academic achievement? *Child Neuropsychology, 18*(1), 79–91. https://doi.org/10.1080/09297049.2011.578572.

Woodcock, R. W., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III tests of achievement.* Itasca, IL: Riverside.