

The Development of Cognitive Skills and Gains in Academic School Readiness for Children From Low-Income Families

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This study examined developmental associations between growth in domain-general cognitive processes (working memory and attention control) and growth in domain-specific skills (emergent literacy and numeracy) across the prekindergarten year and their relative contributions to kindergarten reading and math achievement. One hundred sixty-four Head Start children (44% African American or Latino; 57% female) were followed longitudinally. Path analyses revealed that working memory and attention control predicted growth in emergent literacy and numeracy skills during the prekindergarten year and that growth in these domain-general cognitive skills made unique contributions to the prediction of kindergarten math and reading achievement, controlling for growth in domain-specific skills. These findings extend research highlighting the importance of working memory and attention control for academic learning, demonstrating the effects in early childhood, prior to school entry. Implications of these findings for prekindergarten programs are discussed, particularly those designed to reduce the school readiness gaps associated with socioeconomic disadvantage.

Keywords: cognitive skills, executive functions, school readiness, reading achievement, math achievement

Young children's preparedness to succeed at the academic and behavioral demands of school has been a focus of developmental and educational research for many decades. Recently, legislation such as the No Child Left Behind Act, which holds schools accountable for students' academic performance, has resulted in a heightened interest in better delineation and understanding of the diverse skills that contribute to children's academic success and failure. Of particular concern are the delays in school readiness often experienced by children growing up in poverty. There are substantial achievement gaps between middle-income children and low-income children at school entry that widen over time and contribute to serious disparities in learning difficulties, educational attainment, and long-term employment potential (Ryan, Fauth, & Brooks-Gunn, 2006). Flagship programs, such as Head Start, and rapidly emerging programs, such as public school prekindergarten, are designed to reduce these disparities by enhancing school readiness.

Significant questions remain, however, concerning optimal prekindergarten school practices for economically disadvantaged children (Love, Tarullo, Raikes, & Chazan-Cohen, 2006). On the one hand, evidence that emergent literacy and numeracy skills are

strong predictors of later reading and math achievement (Duncan et al., 2007) suggests that prekindergarten programs for children from low-income homes might reduce school readiness disparities most effectively by focusing more time on direct instruction designed to build skills in these specific domains (Lonigan, Burgess, & Anthony, 2000). On the other hand, developmental research suggests that the preschool years represent a critical period for the development of the mental processes that support effective, goal-oriented approaches to learning, particularly working memory and attention control. These mental processes are often delayed in children growing up in poverty (Noble, McCandliss, & Farah, 2007) and appear to play a central role in predicting school adjustment and academic attainment (Blair & Razza, 2007; Li-Grining, 2007; McClelland et al., 2007). Prior research conducted with elementary school students has suggested that working memory and attention control play a key role in supporting emergent literacy and mathematical computation and problem-solving skills (Fuchs et al., 2005; Passolunghi, Vercelloni, & Schadee, 2006; Swanson & Sachse-Lee, 2001). However, educational research has rarely examined these skills in the context of longitudinal studies or during early childhood when they are undergoing rapid growth.

The goal of the present study was to extend the existing educational research downward developmentally and examine the early childhood precursors of reading and math achievement in kindergarten. Specifically, we sought to understand the association between rapidly developing executive function skills (particularly working memory and attention control) and the acquisition of domain-specific emergent literacy and numeracy skill acquisition during the prekindergarten year. Furthermore, we sought to assess the degree to which growth in those executive function skills during prekindergarten made unique contributions to kindergarten achievement, when growth in domain-specific skills and language

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skills was controlled. We followed a large sample of children in Head Start, measuring these cognitive skills at three time points: beginning and the end of the prekindergarten year and end of the kindergarten year. Two central hypotheses were tested: (a) that growth in working memory and attention control would be associated concurrently with growth in emergent literacy and numeracy skills over the course of the prekindergarten year and (b) that growth of domain-general (working memory, attention control) and domain-specific (emergent literacy and numeracy) skills during the prekindergarten year would each make unique contributions to reading and math achievement in kindergarten.

Early Childhood Developmental Research

Developmental research suggests that working memory and attention control undergo rapid development during the preschool years and have a substantial impact on children's developing "approaches to learning" and corresponding academic achievement (Blair, 2006; Diamond, Barnett, Thomas, & Munro, 2007). Much of this research has focused on the role that cognitive control capacities, often referred to as executive functions, play in fostering the child's capacity for self-regulated and goal-oriented learning. As a group, executive function skills, including working memory, attention set shifting, and inhibitory control, all show substantial development during the preschool years (ages 3–5). Conceptually, these skills enable children to organize their thinking and behavior with increasing flexibility, decrease their reactive responding to contextual cues and contingencies, and engage in self-regulated and rule-governed behavior (Barkley, 2001; Blair, 2006; Blair & Diamond, 2008; Gathercole et al., 2008; Stuss & Alexander, 2005). By promoting children's capacity to inhibit prepotent or impulsive responses and choose alternative responses, these cognitive control capacities enable children to regulate the emotions that motivate and inform their exploration of their physical and social worlds (Derryberry & Rothbart, 1997; Kochanska, Murray, & Harlan, 2000). Developmental researchers have postulated that executive function skills, particularly working memory and attention control, thus facilitate school readiness and early learning by supporting behavioral self-regulatory capacities and social competence (Blair, 2002; C. Hughes & Ensor, 2007) and by fostering children's capacities to engage more effectively with teachers and peers in classroom learning activities (Gathercole et al., 2008; Hamre & Pianta, 2005; Ladd, Birch, & Buhs, 1999).

In this article, we use the term *executive function skills* to refer primarily to working memory and attention control, which theoretically are central cognitive regulatory processes (Friedman et al., 2006) that underlie adaptive, goal-directed responding to novel or challenging situations (C. Hughes & Graham, 2002). At older ages, executive function skills are often thought of as a set of dissociable component abilities (Garon, Bryson, & Smith, 2008; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). However, whether due to measurement difficulties or due to a true lack of differentiation at this developmental stage, researchers have found it difficult to separate these components empirically during early childhood. For this reason, researchers often conceptualize this set of executive function skills as a group (e.g., C. Hughes & Ensor, 2007; Wiebe, Espy, & Charak, 2008). Furthermore, whereas developmental researchers studying early childhood have sometimes focused on the motivational and behavioral benefits of

executive function skills for school readiness (McClelland et al., 2007), educational researchers studying older children have documented a central role for both working memory and attention control in academic learning (Fuchs et al., 2005; Geary, 2003).

Working Memory, Attention Control, and Academic Skill Acquisition in Children

Working Memory

Working memory enables the retrieval of knowledge stored in long-term memory and its mental manipulation and application to foster the interpretation of novel information and the solution of problems (Swanson, Jerman, & Zheng, 2008). Previous research has demonstrated the link between working memory and reading ability in both disabled and nonimpaired readers; moreover, growth in working memory is related to reading comprehension skills in elementary school age children (Gathercole, Tiffany, Briscoe, & Thorne, 2005; Swanson & Jerman, 2008). In addition, a number of studies with school age children suggest that working memory promotes mathematical abilities, including both computation (adding and subtracting) and more complex word problems, and that deficits in working memory are associated with low levels of mathematics performance (Andersson, 2006; Geary, Hoard, Byrd-Craven, Nugent, & Numtee, 2007; Swanson & Sachse-Lee, 2001). Most of the research linking working memory and academic achievement is cross-sectional, but two recent longitudinal studies have documented developmental contributions, with working memory acting as a precursor to later domain-specific achievement. Specifically, Swanson and colleagues (Swanson & Jerman, 2007; Swanson et al., 2008) followed children from Grades 1–3 and found that early working memory supported the development of children's problem-solving abilities, independent of the influence of the phonological system and long-term memory. When children with reading disabilities were identified within that sample, analyses revealed that working memory, but not short-term memory, was related to growth in reading comprehension and reading fluency, documenting that deficient growth in the executive component of working memory underlies reading disability (Swanson & Jerman, 2007). In a second study, Passolunghi et al. (2006) documented predictive links between children's working memory skills at school entry, reflected in their Backward Digit Span performance, and their subsequent math achievement.

Attention Control

Attention control includes the capacity to focus and flexibly shift attention, as well as to ignore irrelevant stimuli and inhibit prepotent responding to stimuli, in order to respond to task demands (Blair & Diamond, 2008). Attention set shifting has shown unique associations with reading among students in elementary school (van der Sluis, de Jong, & van der Leij, 2006).

Research with students who have mathematical difficulties has revealed that many have trouble controlling their attention focus and inhibiting irrelevant information; poor problem solvers remember less relevant and more irrelevant information than good problem solvers (Passolunghi & Cornoldi, 2000). Swanson (2006) found that inhibitory control of attention played a particularly important role in predicting child computational abilities. Bull and

Scerif (2001) found that tasks assessing inhibitory control of attention and attention set shifting (in addition to working memory) made independent contributions to math achievement for first-grade children. Using teacher ratings to assess attention skills, Fuchs and colleagues (Fuchs et al., 2005, 2006) found elevated levels of inattentive behavior among students experiencing math learning difficulties. Furthermore, inattentive behavior, along with working memory deficits, played a central role predicting the emergence of computational and problem-solving mathematical difficulties over the course of the first-grade year. Perhaps reflecting their interacting executive control functions, deficits in attention control and working memory often co-occur among young elementary school children, such that a majority of children with low working memory show high rates of inattentive behaviors including short attention spans and distractibility (Gathercole et al., 2008).

Preschool Educational Strategies to Promote School Readiness

Most current efforts to enhance the impact of prekindergarten education on school readiness for economically disadvantaged children have focused on improving domain-specific instruction to foster the acquisition of emergent literacy and numeracy skills (Konold & Pianta, 2005). Certainly, these efforts are important. Emergent literacy during the preschool period, including the ability to manipulate phonemes and to recognize letters and letter sounds, predicts later reading achievement (Bradley & Bryant, 1983; Bryant, MacLean, Bradley, & Crossland, 1990; Duncan et al., 2007; Lonigan et al., 2000; Wagner & Torgesen, 1987). Similarly, emergent numeracy skills in preschool, including counting, number knowledge, estimation, and number pattern facility, predict later mathematical competence in the elementary grades (Duncan et al., 2007; Geary, 2003; Geary, Hoard, & Hamson, 1999; Jordan, Kaplan, Oláh, & Locuniak, 2006).

These associations are very important for understanding educational progress; however, not to the exclusion of domain-general processes. A limited focus on domain-specific instruction may be short-sighted given the potential importance of domain-general cognitive control processes, such as working memory and attention control, that promote early advances in learning and lead to later advances.

To date, only a few studies have actually examined predictive links between these executive function skills in preschool children and their later academic outcomes. Blair and Razza (2007) and Espy et al. (2004) each found links between tasks requiring inhibitory control of attention and preschool children's numeracy skills, after controlling for IQ. More specific developmental research is needed to better understand the developmental interplay between domain-specific learning in emergent literacy and math skills and growth in these executive function skills over the prekindergarten year, in order to better inform educational strategies designed to foster school readiness.

The Present Study

The current study sought to extend research on the contributions of different cognitive skills to the early academic achievement of low-income children. In particular, we were interested in deter-

mining whether growth in working memory and attention control across the prekindergarten year would predict concurrent growth in emergent literacy and numeracy skills. In line with the theoretical and empirical literature (Blair, 2006), we anticipated that growth in domain-specific skills (emergent literacy and emergent math) and domain-general executive cognitive processes (working memory and attention control) would be related to each other during the prekindergarten year. Second, we hypothesized that growth in both executive functions and emergent academics would make unique contributions to reading and math achievement at the end of kindergarten. In testing these hypotheses, this study had several advantages. First, it included a sample of low-income children. Because these children are most likely to be at risk for problems with school readiness, it is especially important to understand the factors that might compound or remediate their early learning delays. Second, this study relied on measures that have been widely used with preschool children. Third, we assessed cognitive skills at three time points (at the beginning of the prekindergarten year, at the end of the prekindergarten year, and at the end of kindergarten); this allowed for the examination of transactional developmental influences during the prekindergarten year, and it allowed for the examination of the shared and unique impact of growth in cognitive skills during the prekindergarten year on academic achievement at the end of kindergarten. Fourth, in these developmental models, we included controls for children's developing language skills, in order to verify that associations were not simply due to the common factor of advancing language ability (Jordan, Levine & Huttenlocher, 1995; Swanson, 2006).

Method

This study relied on data from the children in the control group of the Head Start Research-based, Developmentally Informed (REDI) project (Bierman, Domitrovich, et al., 2008). All the children in this study received the usual practice Head Start curriculum rather than the enhanced experimental curriculum that was the focus of the REDI intervention trial.

Participants

Participants included 164 children from Head Start classrooms in three Pennsylvania counties (14% Latino American, 30% African American, 56% European American; 57% girls). At the beginning of the school year, brochures describing the study were sent home to the parents of the children who were expected to enter kindergarten the following year; 86% of the eligible children received parental permission and were present for assessments. At the beginning of the Head Start year, children were 4.49 years old ($SD = 0.31$; range: 3.72–5.65).

The families all met the requirements for participation in Head Start; 68% had incomes below the national poverty level. Forty percent of the children lived in two-parent families, 43% lived with single mothers, and 17% lived with relatives or foster families. Overall, 33% of mothers had not completed high school, 46% had a graduate-equivalent degree or high school diploma, 19% had some technical training, and 2% had graduated from college.

Procedures

Child assessments were conducted in the Head Start centers or schools by research assistants during individual "pull-out" sessions

that lasted 30–45 min each. The research assistants participated in a 3-day workshop to learn to administer the measures. They then completed at least two practice assessments in which they were observed by a supervisor and provided with detailed feedback. Assistants had to surpass rigorous standards before collecting data on their own. Throughout all the data collection periods, the research assistants were closely monitored to ensure ongoing adherence to the assessment protocol.

Measures

Child assessments were conducted at three time points: (a) the beginning of the prekindergarten year, as soon as children had acclimated to the classroom setting, (b) the end of the prekindergarten year, and (c) the end of kindergarten. At each time point, measures were collected to assess domain-specific cognitive skills in the area of emergent literacy and emergent numeracy, and domain-general executive cognitive processes associated with learning, specifically working memory and attention control.

Domain-specific emergent literacy skills and reading achievement. Three measures were used to assess emergent literacy skills during the prekindergarten year, selected based on prior research demonstrating predictive relations with children's later reading achievement: the Print Knowledge, Blending, and Elision scales of the Test of Preschool Early Literacy (Lonigan, Wagner, Torgesen, & Rashotte, 2007). In the Print Knowledge subtest, children identified pictures of letters or words and named letters ($\alpha = .95$). In the Blending subtest, which assessed phonological processing, children were asked to combine different parts of a word, such as *hot* and *dog* or *b* and *air*, and point to the correct picture or say the full word ($\alpha = .83$). On the Elision subtest, children deconstructed compound words, such as *snowshoe* without *snow* or *airport* without *air*, and pointed to the correct picture ($\alpha = .80$). Prior research has reported correlations in the range of .43–.88 between these three subscales and the acquisition of initial reading skills (Bradley & Bryant, 1983; Bryant, MacLean, Bradley, & Crossland, 1990; Duncan et al., 2007; Lonigan et al., 2000; Wagner & Torgesen, 1987). A composite score, which averaged standardized scores on Print Knowledge, Blending, and Elision, was computed to represent emergent literacy skills during the prekindergarten year.

Four measures were used to assess reading achievement at the end of kindergarten. The Letter–Word Identification and Story Recall subtests from the Woodcock–Johnson III Tests of Achievement (Woodcock, McGrew, & Mather, 2001) provided nationally normed and standardized scores reflecting children's decoding skills and memory for story content. The Sight Word Efficiency scale of the Test of Word Reading Efficiency (Torgesen, Wagner, & Rashotte, 1999) assessed the number (log-transformed to correct for skewness and kurtosis) of printed words that children identified accurately within 45 s ($\alpha > .80$). The Phonemic Decoding Efficiency scale of the Test of Word Reading Efficiency assessed the number (log-transformed) of nonwords that children sounded out accurately within 45 s ($\alpha > .80$). The Test of Word Reading Efficiency has been used in other research studies with children in kindergarten and has been demonstrated to be both reliable and valid (Byrne et al., 2007; Samuelsson et al., 2007). All four scales

were standardized and averaged into a composite score representing reading achievement at the end of kindergarten.

Domain-specific emergent numeracy skills and math achievement. The Applied Problems scale of the Woodcock–Johnson III Tests of Achievement (Woodcock et al., 2001) required children to perform tasks assessing their understanding of numbers and quantity, such as showing two fingers, counting objects, and adding or subtracting small numbers ($\alpha = .82$). This nationally normed and standardized test has extensive data regarding its reliability and validity (Woodcock et al., 2001). Because children at different ages and with different abilities receive different items on this test, it was used at all three time points to assess initially emergent numeracy skills and later math achievement.

Domain-general cognitive abilities. Three tests were administered to assess general executive cognitive abilities associated with learning. The Backward Word Span required children to listen to a list of words read aloud and then to repeat the words in reverse order (Davis & Pratt, 1996). The requirement to recall words in reverse order imposes a significant working memory processing load on children, requiring them to hold information in mind while they manipulate it mentally. Children received a score of 0 if they could not do the task at all, a score of 1 if they could repeat two words in reverse order, and a score of 2 if they could repeat more than two words in reverse order. Prior research has demonstrated that the Backward Word Span can be used to assess working memory effectively in preschool children (Carlson, 2005; Davis & Pratt, 1996).

The Peg Tapping task (Diamond & Taylor, 1996) required children to tap a wooden dowel twice when the experimenter tapped once and to tap once when the experimenter tapped twice. After practice trials, the child was administered a series of 16 mixed one-tap and two-tap trials ($\alpha = .94$). Successful performance of the task requires children to inhibit a natural tendency to imitate the action of the experimenter while remembering the rule for the correct response. As such, this task assesses inhibitory attention control, reflecting the capacity for the child to inhibit the prepotent response of imitation and replace it with the planned alternative response (Diamond, Prevor, Callender, & Druin, 1997).

The Dimensional Change Card Sort (DCCS; Frye, Zelazo, & Palfai, 1995) used cards depicting blue and red rabbits and boats. Initially, children were taught to sort the cards based on color or shape, in a counterbalanced design. Then, after 12 trials, the children were asked to sort the cards based on the other dimension for the remaining 6 trials. Thus, children were required to flexibly shift their attentional set and inhibit the previously reinforced response in favor of the new one, receiving one point for each of the postswitch trials they sorted correctly ($\alpha = .95$). For preschool children, performance on this task reflects their attention-set-shifting abilities, reflecting both their attention and inhibitory control capacity (Zelazo, Müller, Frye, & Marcovitch, 2003).

On the basis of prior developmental research, we anticipated that these measures of working memory and attention control would be related to and reflect domain-general cognitive control abilities in preschool children. Correlations among the three measures ranged from .26 ($p < .001$) to .35 ($p < .001$). Exploratory factor analyses revealed a single factor, suggesting that, at this age, working memory and attention control share considerable variance and have not been well differentiated. At the beginning of the prekindergarten year, the factor loadings for Backward Word

Span, Peg Tapping, and DCCS were .75, .76, and .65, respectively; at the end of the prekindergarten year, these factor loadings were .75, .73, and .72, respectively. Given these findings, we adopted the approach of other researchers examining similar skills at this age (e.g., C. Hughes & Ensor, 2007; Wiebe, Espy, & Charak, 2008) and created one composite measure of executive function skills for each assessment period, by standardizing and averaging scores on these three tasks.

Language skills covariate. Because of the importance of language skills to children's ability to take advantage of a pre-school curriculum and to their academic achievement in both reading and math, we wanted to be able to covary functioning in this domain at the beginning and end of the prekindergarten year. To do this, we assessed vocabulary, using the Expressive One-Word Picture Vocabulary Test, on which children gave the word that best described pictures they were shown ($\alpha = .93$; Brownell, 2000). We also administered two subscales of the Test of Language Development-Revised (Hammill & Newcomer, 1997). The Grammatical Understanding subtest assessed syntax comprehension by having children listen to a sentence and choose one of four pictures that best matched its meaning ($\alpha = .64$). The Sentence Imitation subtest assessed syntax expression by having children repeat sentences read aloud by the interviewer; scores reflected the number of increasingly complex sentences a child imitated correctly ($\alpha = .86$). Prior research has documented strong test-retest reliability for the Test of Language Development subtests ($r = .90$) and concurrent validity with comprehensive language assessments (Hammill & Newcomer, 1997). All three scales were standardized and averaged into composite scores for language skills at the beginning and end of the prekindergarten year.

Results

To examine associations among domain-specific emergent literacy skills, domain-specific emergent numeracy skills, and domain-general executive functions during the prekindergarten year, we first computed zero-order correlations. These correlations, which were all statistically significant at the .001 probability level, are presented in Table 1. These correlations revealed highly

Table 1
Zero-Order Correlations Between Measures of Prekindergarten Cognitive Functioning

Measure	1	2	3	4	5
1. Beginning of prekindergarten emergent literacy skills					
2. End of prekindergarten emergent literacy skills	.62				
3. Beginning of prekindergarten early numeracy skills	.55	.51			
4. End of prekindergarten early numeracy skills	.47	.47	.60		
5. Beginning of prekindergarten executive function skills	.65	.61	.50	.44	
6. End of prekindergarten executive function skills	.61	.63	.58	.51	.65

Note. All correlations are statistically significant at the .001 probability level.

significant relations among all cognitive variables and considerable stability for both domain-specific and domain-general cognitive skills from the beginning to the end of prekindergarten.

To determine whether the cognitive skill composites, as assessed during the prekindergarten year, predicted reading and math achievement at the end of kindergarten, we also computed zero-order correlations. These correlations, which were all statistically significant at the .001 probability level, are presented in Table 2. As expected, prekindergarten emergent literacy skills significantly predicted kindergarten reading achievement ($r = .40-.48$), and prekindergarten emergent numeracy skills significantly predicted kindergarten math achievement ($r = .53-.54$). In addition, prekindergarten executive function skills (working memory and attention control composite) predicted kindergarten reading achievement ($r = .32-.52$) and kindergarten math achievement ($r = .39-.58$).

Next, we estimated a series of path models predicting kindergarten reading and math achievement. These path models tested the hypothesis that growth in domain-general cognitive skills (working memory and attention control) during the prekindergarten year would make unique contributions to growth in emergent literacy and math skills (accounting for initial levels of functioning in each area). These path models also tested the hypothesis that prekindergarten growth in domain-general cognitive skills would make unique contributions to kindergarten reading and math achievement, after controlling for prekindergarten growth in domain-specific skills and language skills. We relied on full-information maximum likelihood estimation, although there were very little missing data in our sample ($n = 156-161$ for the individual composite measures; 93% of the sample had complete data).

Longitudinal Model Predicting Kindergarten Reading Achievement

Initially, we estimated a saturated path model to predict kindergarten reading achievement in which all independent variables (initial and end-of-year prekindergarten emergent literacy, numeracy, executive function, and language skills) were allowed to affect one another and the outcome and fit the data perfectly. So that our path diagram would be clearer, we eliminated, one by one, all paths that were not statistically significant at the .05 probability level or higher: final model, $\chi^2(6) = 10.35$, *ns*, comparative fit index = .99, Tucker-Lewis index = .97, root-mean-square error of approximation = .07. Controls for language skills remained in place but are not shown in the diagram.¹

The results for this path model are presented in Figure 1. These results show that initial levels of executive functions predicted growth in emergent literacy skills between the beginning and end of the prekindergarten year ($\beta = .29$), with initial levels of emer-

¹ The coefficients in this reduced path model were not substantively different from the coefficients in the saturated model. These coefficients also were not significantly different from those produced in a replication based on 192 children in the intervention sample from Head Start REDI. A multigroup analysis suggested model invariance across children in the control sample (who were included in this study) and children in the intervention sample (who were not included in this study), $\chi^2(15) = 18.51$, $p = .24$.

gent literacy skills (and initial levels of language skills) accounted for.

Predictions to kindergarten reading achievement appear on the right side of Figure 1. The standardized partial regression coefficients represent each cognitive skill composite's unique contribution to children's reading achievement at the end of kindergarten, once the contribution of all other factors in the model has been accounted for. (Because we include both beginning and end of prekindergarten assessments of children's cognitive skill composites in this model, the relation between the end of prekindergarten skill composite and kindergarten reading achievement represents residualized change or growth in the skill composite during the prekindergarten year; the effect of the initial level, as represented by the beginning of prekindergarten assessment, already has been accounted for.) Growth in emergent literacy skills during Head Start predicted kindergarten reading achievement ($\beta = .25$). Moreover, growth in executive functions during the prekindergarten year had an additional, unique influence on kindergarten reading achievement ($\beta = .36$), controlling for the effect of growth in emergent literacy skills during that same period. Thus, consistent with our hypothesis, both domain-specific and domain-general cognitive skills made unique contributions to children's kindergarten reading achievement.

Longitudinal Model Predicting Math Achievement

Parallel to the model predicting reading achievement, we estimated a path model predicting math achievement at the end of kindergarten. Once again, we started with a saturated model but eliminated all paths that were not statistically significant at the .05 probability level or higher: final model, $\chi^2(6) = 10.49$, *ns*, comparative fit index = .99, Tucker–Lewis index = .96, root-mean-square error of approximation = .07.²

The results for this path model are presented in Figure 2. These results show that initial levels of executive functions predicted growth in emergent numeracy skills during the prekindergarten year ($\beta = .20$), with initial levels of emergent numeracy skills accounted for. It is interesting that a reciprocal relation also

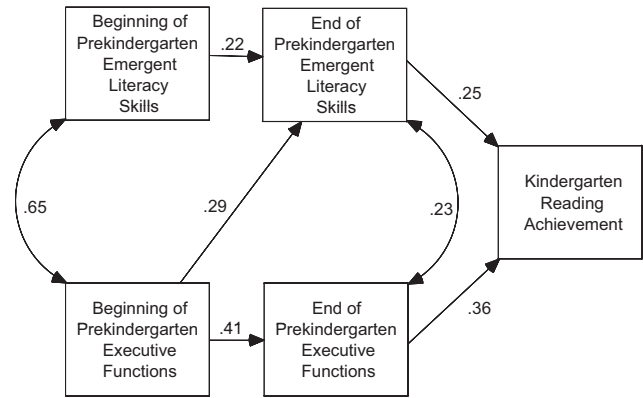


Figure 1. Path model for kindergarten reading achievement.

emerged, such that initial levels of emergent numeracy skills predicted growth in executive functions during the prekindergarten year ($\beta = .21$), with initial levels of executive functions controlled.

Predictions to kindergarten math achievement appear on the right side of Figure 2. In this case, both initial levels of emergent numeracy skills and growth in emergent numeracy skills during the prekindergarten year made unique contributions to kindergarten math achievement ($\beta = .19$ and $.25$, respectively). Moreover, growth in executive functions during the prekindergarten year had an additional, unique influence on kindergarten math achievement ($\beta = .35$), controlling for the effect of growth in emergent numeracy skills during that same period. Just as with kindergarten reading achievement, both domain-specific and domain-general cognitive skills made unique contributions to children's kindergarten academic achievement.

Discussion

Path models revealed concurrent associations between growth in domain-general cognitive skills (working memory and attention control) and growth in domain-specific emergent literacy and numeracy skills during the prekindergarten year. Specifically, working memory and attention control assessed at the start of the year significantly predicted growth in the child's domain-specific skills over the course of the prekindergarten year, after controlling for initial domain-specific and language skills. In this regard, the present study replicates and extends prior research (McClelland et al., 2007) and suggests that early executive function skills contribute to the development of emergent literacy and numeracy skills during the prekindergarten year.

Furthermore, growth in working memory and attention control skills during the prekindergarten year made unique contributions to kindergarten reading and math achievement, after controlling for concurrent growth in the domain-specific skills and language skills. These findings extend previous research documenting a predictive relation between executive functions and later academic

Table 2

Zero-Order Correlations Between Measures of Prekindergarten Cognitive Functioning and Kindergarten Academic Achievement

Measure	Kindergarten reading achievement	Kindergarten math achievement
Beginning of prekindergarten emergent literacy skills	.40	.50
End of prekindergarten emergent literacy skills	.48	.48
Beginning of prekindergarten early numeracy skills	.40	.54
End of prekindergarten early numeracy skills	.44	.53
Beginning of prekindergarten executive function skills	.32	.39
End of prekindergarten executive function skills	.52	.58

Note. All correlations are statistically significant at the .001 probability level.

² Again, the coefficients in this reduced path model were not substantively different from the coefficients from the saturated model, and they were not significantly different from those produced in a replication based on the children in the intervention sample, $\chi^2(15) = 19.92$, $p = .18$.

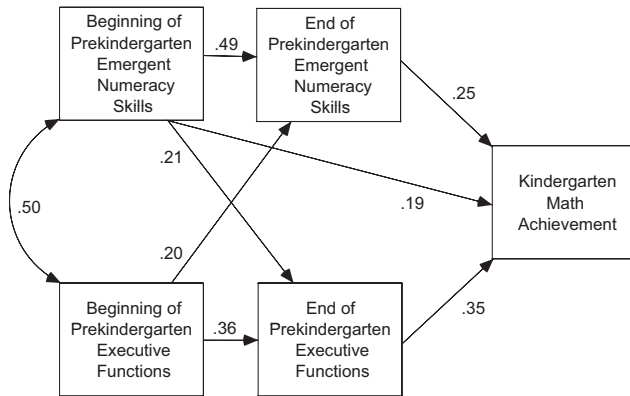


Figure 2. Path model for kindergarten math achievement.

competencies (Blair & Razza, 2006; Bull & Scerif, 2001; Espy et al., 2004; Gathercole et al., 2005; Swanson et al., 2008). Importantly, these findings suggest that the early development of working memory and attention control provides an important foundation for domain-specific academic learning. A unique contribution of this study was the assessment of cognitive skills at three time points (two prior to school entry), allowing exploration of transactional developmental influences on the precursors of early reading and math achievement, over the course of the prekindergarten year and the transition into kindergarten.

Prior research on executive functions with preschool children has emphasized the contribution that executive function skills make to children's developing self-regulation and behavioral readiness for school, leaving the impact on prekindergarten and kindergarten learning and achievement relatively unexplored (Blair, 2006; J. N. Hughes & Kwok, 2006). The self-regulation hypothesis is that growth in working memory and attention control during the preschool years promotes children's capacity to follow classroom rules, regulate affect, sit still, and learn on demand through listening and watching (McClelland et al., 2007). In addition, these skills are thought to underlie goal-oriented motivation and to support adaptive approaches to learning, including learning initiative and efficacy motivation (Normandeau & Guay, 1998).

On the other hand, prior research on working memory and attention control among elementary school age students has primarily emphasized the cognitive capacity and control achieved with executive function skill development, rather than the behavioral correlates. These skills improve the retrieval of information from long-term memory and support the sustained mental representation and focused manipulation of key information for problem solving and learning (Davidson, Amso, Anderson, & Diamond, 2006). Particularly during early childhood, when executive function skills are first developing, it may be important to keep both cognitive and emotional-behavioral regulatory functions in mind when considering how these skills contribute to school readiness (Blair & Diamond, 2008).

Reciprocal Relations With Numeracy Skills

One additional, interesting finding that emerged in this study was evidence that prekindergarten numeracy skills, but not emergent literacy skills, made unique, reciprocal contributions to the

growth of prekindergarten executive function skills. That is, early emergent numeracy skills predicted later executive functions (controlling for initial executive functions), as well as the reverse (e.g., early executive functions predicting later emergent numeracy skills, controlling for initial numeracy skills). This reciprocal relation is of interest given growing evidence for a close association between working memory, attention control, and ability in mathematics (Blair & Razza, 2007; Bull & Scerif, 2001). It might reflect the degree to which prekindergarten math activities, particularly in comparison with prekindergarten literacy activities, make demands on working memory and attention control, such as the ability to hold relevant information in mind, to operate on it while shifting attention appropriately among problem elements, and to inhibit automatic or prepotent responding to only one aspect of a given problem (Blair, Gamson, Thorne, & Baker, 2005). These findings are important given that early mathematical ability is a robust predictor of later academic achievement in both math and reading (Duncan et al., 2007).

Although initial levels of executive functions predicted growth in emergent literacy skills during the prekindergarten year, the reverse was not true. Emergent literacy skills represent acquired, acculturated knowledge or crystallized abilities. Our data suggest that this kind of knowledge is not related to growth in the domain-general executive functions of working memory and attention control.

Implications for Prekindergarten Academic Curricula

In both reading and math domains, kindergarten achievement was uniquely predicted by prekindergarten growth in the domain-specific skills (e.g., emergent literacy and emergent numeracy skills, respectively). Learning that occurs in these domains during the preschool year has a positive impact on children's academic progress in kindergarten.

These findings provide support for the current efforts to enrich domain-specific preacademic curricula in Head Start and other high-quality preschool programs. In general, the quality of instructional content to which a child is exposed is an important determinant of domain-specific knowledge acquisition in the areas of emergent literacy and numeracy skills (Konold & Pianta, 2005). Hence, enriching domain-specific academic curricula in prekindergarten classrooms is likely to enhance academic readiness (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Lonigan et al., 2000).

Promoting Executive Functions in Prekindergarten

The finding that growth in executive function skills during the prekindergarten year enhanced the prediction of kindergarten achievement in both reading and math suggests that children might benefit if prekindergarten programs also made concerted efforts to promote the development of working memory and attention control. The challenge is that, at present, much less is known about how preschool programs can promote these kinds of skills than is known about the optimal scope and sequence of emergent literacy and math skill instruction.

One approach to the promotion of working memory and attention control skills involves providing children with repeated practice sessions on specific executive function tasks (Klingberg,

Forssberg, & Westerberg, 2002; Parasuraman & Giabra, 1991; Reisberg, Baron, & Kemler, 1980; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). Experimental studies with older children show that performance on executive function tasks can be improved in this manner, and there is some evidence that computer-based training focused on inhibitory control and attention set shifting may promote those skills along with improved behavioral control among older children with attention-deficit/hyperactivity disorder (Klingberg et al., 2005). However, it remains unclear whether these types of cognitive training activities are appropriate for preschool children or whether they will promote generalized learning gains in the classroom setting. No studies have yet demonstrated the benefits of computer-based training for preschool children or linked these improvements to changes in academic skills.

Complementary to an intervention approach that focuses on cognitive training, interventions designed to promote self-regulation skills and social-emotional learning show some promise for promoting executive function skill development in young children (Bierman, Nix, et al., 2008; Diamond et al., 2007; Riggs, Greenberg, Kusché, & Pentz, 2006). This intervention approach is based on developmental research that suggests that socialization experiences play an important role in supporting the development of executive functions. For example, developmental research suggests that executive function skill development is significantly affected by the availability of sensitive-responsive caregiving, support for sustained joint attention, and effective scaffolding of early emotion regulation (Cicchetti, 2002; Goldsmith & Rogoff, 1997; Lengua, Honorado, & Bush, 2007). Socioeconomic disadvantage is associated with delays in such skill development, possibly because children growing up in poverty are likely to experience more stress, less sensitive-responsive caregiving, and low levels of cognitive stimulation (Lengua et al., 2007; Li-Grining, 2007). In addition, children who experience extreme adversity in their early years, such as maltreatment or severe neglect, show deficits in attention control (Cicchetti, 2002; O'Connor et al., 2000). Researchers have postulated that the experience of traumatic events affects neuroendocrine and autonomic stress reactivity, increasing the demands on executive regulatory systems (Cicchetti, 2002), thereby impeding development and functioning.

Parallel to this research, several recent intervention trials have demonstrated that psychosocial interventions designed to promote the self-regulation skills of young children also produce positive effects on the development of attention control skills, including improvements on the Stroop and DCCS tasks, and improved learning engagement (by observer report; Bierman, Nix, et al., 2008; Diamond et al., 2007; Riggs et al., 2006). For example, the Promoting Alternative Thinking Strategies (PATHS) program was designed to foster the development of neurocognitive control both vertically (i.e., frontal control of emotion and arousal) and horizontally (i.e., language use in the service of emotion regulation; Greenberg & Kusché, 2006). The PATHS program targets emotion regulation, self-control, and social problem-solving skills and conceptualizes behavioral improvements as having a foundation in the development of the biological substrates involved in self-regulation (Greenberg & Kusché, 1993). Supporting this conceptualization, Riggs et al. (2006) analyzed outcomes from a randomized-controlled trial of PATHS implemented in second and third grade and documented improvements in children's inhibitory

control and verbal fluency. Similarly, in the Head Start REDI project, which used the Preschool PATHS program, intervention produced significant improvements in children's performance on the DCCS task and on a behavioral measure of task orientation. It is interesting that the intervention appeared particularly beneficial to children who started the year with low levels of behavioral inhibitory control (e.g., difficulties delaying motor responding and sustaining effortful task engagement; Bierman, Nix, et al., 2008).

Another preschool program that has demonstrated positive effects on some executive function tasks is the Tools of the Mind (ToM) program (Bodrova & Leong, 1996). In ToM, learning activities are restructured in ways that, theoretically, support greater self-regulatory skill development. Specific strategies include make-believe play planning and social role enactment with emphasis on reciprocal interaction, negotiation, and sustained role playing. Games designed to teach self-regulation and reflective thinking involve turn-taking, inhibitory control, and remembering and carrying out preplanned behaviors over impulsive behaviors. The premise of this program is that play provides a unique opportunity for developing critical self-regulatory skills (Vygotsky, 1933/1962). Research evaluating the ToM program in the context of a randomized trial has shown that children in ToM classrooms perform significantly better on tests of cognitive executive functioning, have better vocabularies, and display fewer teacher-reported behavior problems than children in control classrooms (Diamond et al., 2007).

These are encouraging findings. Clearly, however, more research is needed to determine the optimal strategies for enriching prekindergarten programs in ways that will foster growth in working memory and attention control skills.

Study Limitations

This study had several limitations that must be kept in mind when interpreting the results. One important limitation was that the measurement of working memory and attention control included only three tasks, which were combined to form a composite. Most past research on executive function skills in preschool children has likewise used limited measures and created composite measures (e.g., C. Hughes & Ensor, 2007; Wiebe et al., 2008), because of the difficulty that young children have complying with extended testing sessions. Whether due to the developmental period or due to this limited measurement strategy, we were not able to isolate specific cognitive functions as is often done in studies with older children and adults (Garon et al., 2008; Miyake et al., 2000). However, the tasks that were used in this study are commonly used with preschool children to tap the executive function skills of working memory and attention control that are most closely associated with reading and math achievement (Fuchs et al., 2005; Swanson & Sachse-Lee, 2001). Furthermore, developmental research has indicated that these tasks are sensitive to the rapid growth in these cognitive control skills that occurs during the preschool period (Blair & Diamond, 2008). Given its design, this study does not shed light on the important conceptual and measurement issues regarding executive functions, but the findings do suggest that this set of cognitive skills deserves further research and greater attention in prekindergarten design and evaluation, given evidence of the important role they play in learning.

Second, given the measurement limitations of the study, we could not estimate latent constructs and conduct structural equations models but relied on path analyses to examine developmental processes. We suspect this was partially the result of the measurement challenges in assessing multiple dimensions of cognitive functioning in young children. We also suspect that it might reflect the lack of differentiation that actually exists in some aspects of cognitive functioning in young children. There are few if any studies that have been able to demonstrate much differentiation in such young children in a methodologically rigorous manner. We must rely on the incremental validity of our measures as the best evidence that they are distinct and meaningful domains; it is unlikely they would have uniquely contributed to the prediction of kindergarten academic achievement if they all simply represented general cognitive ability.

Third, the design of this study precludes any firm conclusions about causal effects. Although the longitudinal developmental design is a positive aspect of the study, it can specify only that change in domain-specific and domain-general cognitive skills is related to academic school readiness. It may be that there are underlying processes beyond language development—which was controlled in our study—that are not included in our design but that are responsible for the changes we observed. Experimental evidence would be necessary to make claims about causation.

Conclusions and Implications

The goal of the present study was to extend the existing educational research downward developmentally and examine the contributions of working memory and attention control in early childhood to kindergarten reading and math achievement, while controlling for the contributions of domain-specific emergent literacy and numeracy skills and language skills. The primary contribution of this study is that it examined the relation of change in executive functions during the prekindergarten year to academic outcomes at the end of kindergarten in a sample of children from low-income families. A number of prior studies have examined relations of executive functions to academic outcomes at a single time point or in longitudinal studies beginning at school entry. However, we are not aware of other studies that have examined the relation of change in executive function during preschool to later academic achievement in elementary school. Our developmental data provide compelling evidence that development in working memory and attention control during the preschool period might be an important contributor to later academic achievement in reading and math.

The time is ripe for additional research on the relation between executive functions and school readiness, as many questions remain unanswered. First, it will be important to see whether improvements in executive functions lead to meaningful, consistent, and enduring improvements in academic skills. Second, the relation between executive function training and other aspects of school readiness, such as socioemotional adjustment, should be investigated. Third, research should extend the current knowledge base regarding the development of executive functions. Although the preliminary intervention work on executive functions has focused on early childhood, there is evidence that developmental improvements in working memory and attention control continue throughout childhood and adolescence (Conklin, Luciana, Hooper,

& Yarger, 2007; Luciana & Nelson, 1998). Given this, it would be helpful for educators to know which aspects of executive functions are most relevant for learning and school readiness at particular developmental periods and, relatedly, at which points in development interventions targeting executive functions are most likely to be helpful at promoting academic growth. Finally, our study involved the academic adjustment of children in poverty, a population at high risk for educational failure. Given the finding that executive functions are an aspect of cognitive development particularly likely to be adversely affected by poverty, it may be that poor children would particularly benefit from such interventions. Further research on each of these issues could potentially enhance the quality of early education programs and, in turn, improve the educational outcomes of many children at risk.

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