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Kindergarten Components of Executive Functions and Third Grade Achievement: A National Study

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Study Highlights

This study examines the unique, longitudinal contributions of executive functions and its core components at school entry to end of third grade academic achievement.

Our research design includes multiple measures of executive functions, numerous covariates, and measures of important academic skills.

Evidence for cross-domain achievement associations are strongest for working memory, and stronger for math than reading achievement.

We discuss implications for future studies and consider the measurement issues that arise from using a large-scale dataset to examine EF and its relations to longitudinal achievement.

Abstract

The present study uses nationally-representative data to estimate longitudinal associations between core executive function (EF) components—working memory, inhibitory control, and cognitive flexibility—at kindergarten entry and third grade academic achievement. We focus on one key question: to what extent do EF components uniquely contribute to children's subsequent reading and math achievement over and above academic skills, social-emotional behaviors, and learning-related behaviors? Study findings indicated that the three core EF components have differential associations with third grade achievement. Evidence of associations across domains of math and reading achievement are strongest for working memory, and these associations are stronger for math than reading achievement. Early working memory was also shown to be just as predictive of academic achievement as were learning-related behaviors. The evidence for achievement associations was weaker for inhibitory control and cognitive flexibility, with estimated effect sizes on reading and math achievement of less than a tenth of a standard deviation. We discuss implications for future studies and consider the measurement issues that arise in examining EF and its relations to longitudinal achievement.

Kindergarten Components of Executive Functions and Third Grade Achievement: A National Study

The potential for executive function (EF) to support children's learning and adaptation to the classroom environment makes it an important dimension of school readiness and achievement. Accordingly, research on EF and its applications to educational outcomes has proliferated in recent years. Some of this research has shown that EF skills develop rapidly during childhood (Diamond, Prevor, Callender, & Druin, 1997; Diamond, 2006; Romine & Reynolds, 2005), at a time when many children have also begun formal schooling. EF skills have been shown to be predictive of children's learning and academic achievement (Blair & Diamond, 2008; Blair & Razza, 2007; Bull, Espy, & Wiebe, 2008; Diamond, Barnett, Thomas, & Munro, 2007; Fuhs, Nesbitt, Farran, & Dong, 2014; McClelland & Cameron, 2012; Ursache, Blair, & Raver, 2012), perhaps by fostering children's abilities to engage more effectively in instructional time, free play, and interactions with adults and peers (Blair & Diamond, 2008; Hamre & Pianta, 2005; Ladd, Birch, & Buhs, 1999). Because EF skills are thought to be particularly important for early academic skills development, it is important to understand how these skills develop longitudinally and how they relate to different domains of academic achievement.

The current study examines EF components, along with other indicators of school readiness, including learning-related behaviors, social-emotional behaviors, oral language, and reading and math achievement, to determine whether they predict gains in children's subsequent academic achievement. Specifically, this study assesses the degree to which EF components measured in the fall of kindergarten predict third grade achievement, over and above concurrent correlates of EF, in order to understand the strength and specificity of effects by different academic domains, including reading and math achievement. Below, we review the salient prior work that motivates our hypotheses about the unique contributions of EF components to children's long-run academic achievement.

Associations of EF Components Across Domains of Academic Achievement

EF is generally theorized to be a set of higher order cognitive and regulatory processes that are utilized in problem solving, goal-directed activities, and self-regulation. Most scholars agree on three distinct but related core components of EF: working memory, cognitive flexibility, and inhibitory control (Blair, 2002; Diamond, 2013; McClelland, Cameron Ponitz, Messersmith, & Tominey, 2010; Miyake et al., 2000; Zelazo & Carlson, 2012), and have documented the role of these skills in academic learning. Understanding the nature of these associations is important for the design of interventions that can boost the potential for children's longitudinal achievement.

Working memory. Working memory is the ability to maintain relevant information at the same time despite potential distracting stimuli. This allows children to mentally work with or manipulate that information, making it possible to remember plans and instructions (Hughes & Graham, 2002; Zelazo, Carlson, & Kesek, 2008). In the classroom setting, children must direct attention to important information as they participate in activities, work at a center and keep track of their progress, and remember the order in which things need to be done. This core component of EF has been found to be uniquely associated with learning math skills (Bull & Scerif, 2001; De Smedt et al., 2009; LeFevre et al., 2013; Purpura & Ganley, 2014), comprehending oral language (Adams, Bourke, & Willis, 1999; McClelland et al., 2014), and developing literacy skills (Alloway & Alloway, 2014; St. Clair-Thompson & Gathercole, 2006).

Cognitive flexibility. Cognitive flexibility is the ability to shift between two or more competing response alternatives (Davidson, Amso, Anderson, & Diamond, 2006; Zelazo & Müller, 2002). This includes considering something from a new or different perspective, switching between perspectives, adjusting to change, and thinking abstractly or outside of the box. Cognitive flexibility is important for children to engage in creative problem solving in the classroom or adjust to changing demands or priorities in the classroom environment. Though this core component of EF is likely important for academic achievement, these links have not been studied as much as is the case for working memory, and results from studies examining links between the cognitive flexibility and later achievement are ambiguous. Some studies have found it to be related to math (Clark, Pritchard, & Woodward, 2010; Lan, Legare, Cameron Ponitz, Su, & Morrison, 2011; Yeniad, Malda, Mesman, van IJzendoorn, & Pieper, 2012) and reading (Allan & Lonigan, 2011; Colé, Duncan, & Blaye, 2014; Latzman, Elkovitch, Young, & Clark, 2010; Yeniad et al., 2012), whereas other studies have not (Espy et al., 2004; Lee et al., 2012; van der Sluis, de Jong, & van der Leij, 2007).

Inhibitory control. Inhibitory control is the ability to inhibit one's own response to distractions (Best & Miller, 2010; Davidson et al., 2006; Diamond, 2006). For example, inhibitory control can help children block out distractions from classmates and focus on the task at hand, making possible selective, focused, and sustained attention (Diamond & Lee, 2011; Welsh, Nix, Bierman, Blair, & Nelson, 2010). Although some studies suggest associations between inhibitory control and reading and language comprehension (Blair & Razza, 2007; St. Clair-Thompson & Gathercole, 2009) and mathematical ability (Bull & Scerif, 2001; Clark, et al., 2010; Espy et al., 2004), other studies report no associations with reading (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; McClelland et al., 2014) and math (Monette, Bigras, & Guay, 2011; Swanson, 2006).

There is little consensus in this literature regarding which EF components are predictive of academic achievement. One reason for this discrepancy may be due to the age of the samples as the studies reviewed above focused on preschool and kindergarten. Researchers have shown that EF becomes more differentiated across childhood (Garon et al., 2008; Lee et al., 2013; McAuley & White, 2011), so patterns of associations with academic achievement may change as children's EF skills become more developed. Another possible reason for the discrepancies in the literature is that the tasks used across these studies to measure a particular aspect of EF are quite different or that the tasks may be sensitive to children's age (Morrison & Grammer, 2016). To synthesize the wealth of studies documenting these associations across reading and math domains, we turn to meta-analytic reviews of the literature.

Previous Reviews of EF Components on Achievement

Previous reviews of the literature on EF and academic achievement are informative for describing the relative strengths of their relations, though not all have taken a comprehensive look at all three components of EF. Allan et al. (2014) evaluated the empirical support for the relation between inhibitory control and academic achievement. They found that inhibitory control was more strongly associated with math skills than literacy skills, with associations of .34 for math achievement and .25 for reading achievement. For cognitive flexibility, a meta-analysis by Yeniad et al. (2013) found that correlations for this EF component was significant and similar for reading and math achievement, with associations that ranged from .21 to .26.

Other reviews have examined all three components of EF but focused exclusively on a specific domain of academic achievement. Friso-van den Bos et al. (2013) examined cross-sectional relations between children's EF skills and math achievement and found the components of working memory all to be more strongly associated with math than cognitive flexibility or inhibitory control. In a more recent study, Follmer (2018) examined relations between EF skills and reading comprehension achievement and reported similar associations for working memory (.38) and cognitive flexibility (.39), but smaller associations for inhibitory control (.21).

A meta-analysis by Jacob and Parkinson (2015) focused on all three aspects of EF and reading and math achievement. They found moderate associations of EF components with academic achievement from the most rigorous regression-based studies, with associations being similar across reading and math domains. This study was limited in the collection of covariates in the studies included in their meta-analysis. They conclude in their meta-analysis that more rigorous research is needed to better understand relations between EF and achievement, and in particular, more studies are needed that include strong sets of controls to understand the causal links. Based on recommendations from Jacob and Parkinson (2015), our study presents a more comprehensive picture of the differential relations of children's EF skills in the context of many other indicators of school readiness on third grade academic achievement.

Other Predictors of Academic Achievement

To investigate the role of EF components in predicting children's academic outcomes, it is also important to include other predictors that might play a role in long-run achievement. Duncan et al. (2007) document strong associations between early academic, attention, and learning-related skills and later achievement. Notably, they found that early math is a strong predictor of later reading achievement than early reading is of later math achievement, although subsequent work has questioned the causal nature of these associations (Bailey, Duncan, Watts, Clements, & Sarama, 2017). Children's oral language has also been found to be an important predictor of literacy and math achievement (Purpura, Logan, Hassinger-Das, & Napoli, 2017). Further, children's academic outcomes have been found to be linked to family background characteristics, such as maternal education and early language skills (Magnuson, 2007; Weigel, Martin, & Bennett, 2010). Several other child, family, and other contextual characteristics (e.g., child's race, gender, family structure, family income, quality of home environment) are also consistently predictive of school achievement (e.g., Duncan, Brooks-Gunn, & Klebanov, 1994; NICHD Early Child Care Research Network (ECCRN) & Duncan, 2003; NICHD ECCRN, 2005), so the approach of the current study is to account for these factors in our models to evaluate the net contributions of the core EF components to longitudinal reading and math achievement.

Current Study

The purpose of the current study is to estimate the predictive power of school-entry EF components for reading and math achievement in third grade. We focus on the longer-run links between EF and academic achievement during this time period because kindergarten is a time when teachers and parents hold various different expectations of children (e.g., remaining seated for long periods, sustained attention during instruction) and their learning environments place greater demands on their EF skills (Cuevas, Hubble, & Bell, 2012).

The empirical approach taken in this paper most resembles that taken in the Duncan et al. (2007) analysis of six longitudinal datasets. Associations between children's school readiness skills and later reading and math achievement were estimated for each dataset, controlling for an exceptionally rich set of child, family, and contextual factors to reduce bias in describing the associations between of kindergarten-entry skills and later academic achievement. The novel contributions of the current study are to utilize this approach for school-entry EF and to capitalize on a large, national dataset. Prior studies have often excluded many potential confounding covariates (see Jacob & Parkinson, 2015 for a review). Excluded variables, if positively correlated with both EF and achievement, will impart an upward bias to the estimated role that EF components play in predicting achievement. Thus, the current study uses more conservative statistical techniques to test the associations between EF components and academic achievement.

We attempt to answer one key question in this study: to what extent do EF components uniquely contribute to children's end of third grade reading and math achievement over and above academic skills, social-emotional behaviors, learning-related behaviors and family background? Based on developmental theory and prior research suggesting the specific usefulness of EF skills in supporting children's academic achievement, we hypothesized that all three components of children's EF at school entry will uniquely contribute to the prediction of long-run reading and math achievement (Alloway & Alloway, 2014; Blair & Razza, 2007; Cragg & Gilmore, 2014), even after accounting for the contribution of other school readiness indicators and background characteristics.

For reasons discussed below, the measures of EF used in our study are not without limitations – we have only one measure per EF component and not all measures are assessed directly. However, our study provides a valuable starting point for other evaluations of children's EF in that we have a longitudinal design that includes multiple measures of EF, numerous covariates, and measures two important academic skills – all critical features to be integrated in the research designs of studies examining the relationship between EF and academic achievement (Jacob & Parkinson, 2015; Müller, Liebermann, Frye, & Zelazo, 2008).

Method

Data

The data used in this study come from the Early Childhood Longitudinal Study Kindergarten Class 2010-11 (ECLS-K 2011). Funded by the U.S. Department of Education and overseen by the National Center for Education Statistics (NCES), the ECLS-K 2011 was designed to focus on children's schooling experiences from kindergarten through fifth grade. Data collection included parent interviews, surveys of teachers and school administrators, and direct child cognitive assessments. The ECLS-K 2011 sample comprises approximately 18,000 kindergartners selected from a nationally representative set of 1,330 schools in 90 counties across the U.S (for more information of the ECLS-K 2011, see Tourangeau et al., 2014; IES/NCES requires users of restricted-use data to round all sample sizes to the nearest ten). The students will eventually be followed for six years of school, through the fifth grade.

The analyses for this paper utilize data from students with cognitive test scores from the fall of kindergarten and the spring of third grade. NCES provides sampling weights to compensate for initial and subsequent nonresponse and produce representativeness national estimates through third grade. Item nonresponse was relatively infrequent (mean = 5%, range=0-20%).

Descriptive statistics for the sample are presented in Table 1 and reflect the diversity of kindergartners in terms of demographic characteristics, linguistic background, and socio-economic status. The ECLS-K 2011 oversampled Asian Pacific Islander and Indian/Alaskan children, twins, and children born with low and very low birth weight (Tourangeau et al., 2014). We used the ECLS-K sampling weights for all descriptive and substantive analyses. Children in the analysis samples were predominantly non-Hispanic White (50%), non-Hispanic African-American (13%), and Hispanic (26%). The analysis sample also includes 15% of children whose home language is not English.

[INSERT TABLE 1]

Measures

The ECLS-K 2011 is unique in providing measures of children's academic achievement, social-emotional skills and behaviors, and EF skills for a large, nationally representative sample.

Two panels of experts, including practitioners, content area experts, and researchers in the fields of education, sociology, and psychology, were established to provide critical reviews of the constructs and content of instruments in the ECLS-K 2011 (Tourangeau, Lê, Nord, Sorongon, 2009; Tourangeau et al., 2014). Reported reliabilities (Cronbach's alpha) for the measures and reports presented in Table 2 were drawn from the ECLS-K 2011 user's manual and technical reports (Tourangeau, et al., 2009; 2014) and corresponding summary statistics are also included.

[INSERT TABLE 2]

Executive Function. Children's EF was assessed in three competencies (inhibitory control, working memory, and cognitive flexibility) and measured with a combination of direct cognitive assessments and teacher reports. All measures were used as the key independent variables in the analyses.

Inhibitory control. Inhibitory control was measured with the Children's Behavior Questionnaire (CBQ) Short Form Inhibitory Control Sub-Scale (Putnam & Rothbart, 2006), a self-administered questionnaire for teachers.[1] Teachers responded regarding how true or not a particular behavior is of the child on a 7-point Likert scale ranging from "extremely true" to "extremely untrue." Sample items for this scale include whether the child "can wait before entering into new activities if s/he is asked to," "has trouble sitting still when s/he is told 'no'." This score was computed as the mean of the items comprising the score. Though inhibitory control is often assessed with direct child assessments, the CBQ has also been used as a reliable measure in prior studies examining EF and school readiness (e.g., Blair & Razza, 2007). The reliability for this assessment in the fall of kindergarten was .87.

[1]Because this was the only measure available for the ECLS-K team to use in order to capture children's inhibitory control, we made the decision to refer to it in the same way they did. This measure is typically referred to as a measure of Effortful Control, which is not necessarily the same; see Zhou, Chen, & Main (2012). We thank an anonymous reviewer for pointing this out.

Working memory. To measure working memory, children were administered the Numbers Reversed subtest of the Woodcock-Johnson III Tests of Cognitive Abilities (Wendling, Mather, & Shrank, 2009). In this task, the assessor reads increasingly longer series of numbers to the child, who must repeat the numbers in reverse order. Alloway and Alloway (2014) report that this is a validated method to assess working memory as the benefit of this version is that it does not include a forwards number component and thus measures verbal working memory exclusively. Children's standard score for this measure was used for the current analyses and is normed to their age. This measure has a reported reliability of .87 (Schrank, McGrew, & Woodcock, 2001; Woodcock, McGrew, & Mather, 2001).

Cognitive flexibility. Children were presented with the Dimensional Change Card Sort (DCCS) task as an assessment of their cognitive flexibility (Frye, Zelazo, & Palfai, 1995). Children sort cards into trays based on rules that change in the middle of the task. Children are presented with two target pictures that vary along two dimensions – shape and color. They are asked to match a series of bivalent test pictures (e.g., yellow balls and red trucks) to the target pictures, first according to one dimension (e.g., color) and then, after a number of trials, according to the other dimension (e.g., shape). Though lower than the test-retest reliability of other EF tasks, this measure of cognitive flexibility is widely used in studies predicting achievement in young children and is now a standardized measure in the NIH Toolbox (Weintraub et al., 2013) and has also been used in several studies also examining children's EF and achievement (e.g., Welsh et al., 2010). This measure is reported to have shown excellent test-retest reliability (Beck, Schaefer, Pang, & Carlson, 2011; Zelazo, 2006).

Academic Achievement. Academic achievement scores in reading and math were collected from direct child assessments administered in the fall and spring of kindergarten and the spring of third grade (Tourangeau et al., 2014). These scores were based on item response theory (IRT), which places all children on a common ability scale and are comparable over time. Language screeners were administered to children to determine whether the reading and math assessment would be given in English or Spanish. Because of the adaptive design of the assessments, this allowed for the computation of scores for all children, regardless of home language and English proficiency. For more information on how the assessments were administered, see Tourangeau et al., 2014.

To facilitate interpretation, these scores were converted into standardized units. Spring of third grade reading and math IRT scores were used as the key dependent variables, while fall of kindergarten reading and math IRT scores were used as independent variables. In Table 2, we also present the spring of kindergarten reading and math IRT scores since we will include them in our robustness checks.

Reading achievement. The reading assessment was designed to measure children's basic skills such as print familiarity, letter recognition, beginning and ending sounds, recognition of common words (sight vocabulary), decoding of multisyllabic words, vocabulary knowledge, such as receptive vocabulary and vocabulary-in-context, and reading comprehension. Reading comprehension questions were asked only of children who could read. A number of the items from this assessment were taken directly or adapted from copyrighted instruments, including the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997), Test of Early Reading Ability (Reid, Hresko, & Hammill, 1989), and Test of Preschool Early Literacy (Lonigan, Wagner, Torgesen, & Rashotte, 2007). This measure has a reliability of .95 in the fall of kindergarten and .93 in the spring of third grade.

Math achievement. The math assessment was designed to measure skills in conceptual knowledge, procedural knowledge, and problem solving. The test consisted of questions on number sense, properties, and operations; measurement, geometry, and spatial sense; data analysis, statistics, and probability (measured with a set of simple questions assessing children's ability to read a graph); and pre-algebra skills such as identification of patterns. A number of the items from this assessment were taken directly or adapted from copyrighted instruments, including the Tests of Early Math Ability (Ginsburg & Baroody, 2003) and the Woodcock-Johnson Applied Problems and Calculations subtests (Woodcock et al., 2001). This measure has a reliability of .92 in the fall of kindergarten and .93 in the spring of third grade.

Oral language. Children's oral language was measured with two tasks from the Preschool Language Assessment Scale (preLAS 2000; Duncan and De Avila, 1998) given by the assessor in English. The first task, Simon Says, required children to follow simple, direct instructions. The second task, Art Show, was a picture vocabulary assessment that tested children's expressive vocabulary. The total preLAS score was used as a measure of children's oral language and its reliability in the fall of kindergarten was .91.

Social-emotional Behaviors. Measures of children's socio-emotional skills and behaviors taken at kindergarten entry were included as control variables in the analyses. These skills and behaviors were measured with the Social Skills Questionnaire constructed by the ECLS-K 2011 staff and adapted from the externalizing problem behaviors, internalizing problem behaviors, self-control, and interpersonal skills subscales of the Social Skills Rating System (Gresham & Elliot, 1990). Some items were taken verbatim, some items were modifications, and some were worded differently for the purposes of the ECLS studies. As part of a self-administered questionnaire in the fall of kindergarten, teachers rated students on several items on a 4-point response scale ranging from "never" to "very true." A benefit of teacher reports as a measure of socio-emotional functioning is that they capture children's behaviors within the ecological context of the classroom (Fuhs, Farran, & Nesbitt, 2015).

Externalizing problem behaviors. The five items in this scale asked teachers to rate the frequency with which a child argues, fights, gets angry, acts impulsively, and disturbs ongoing activities. Scores for this scale were reversed so that higher scores indicated better behavior. For the fall of kindergarten, this measure has a reliability of .88.

Internalizing problem behaviors. The four items in this scale asked teachers about the child's apparent presence of anxiety, loneliness, low self-esteem, and sadness. Scores for this scale were reversed so that higher scores indicated better behavior. This measure has a reliability of .79 in the fall of kindergarten.

Self-control. The four items in the self-control scale indicated a child's ability to control behavior by respecting the property rights of others, controlling temper, accepting peer ideas for group activities, and responding appropriately to pressure from peers. For the fall of kindergarten, this measure has a reliability of .81.

Interpersonal Skills. The five items in the interpersonal skills scale rated a child's particular skills in forming and maintaining friendships, getting along with people who are different, comforting or helping other children, expressing feelings, ideas, and opinions in positive ways, and showing sensitivity to others' feelings. This measure has a reliability of .86 in the fall of kindergarten.

Learning-related Behaviors. The ECLS-K 2011 staff constructed an "approaches to learning" scale for teachers to rate children's attention and self-regulatory behaviors. It consists of six items measuring the child's attentiveness, task persistence, eagerness to learn, learning independence, flexibility, and organization. The response scale included four points ranging from "1=never" to "4=very often" to indicate how frequently the child exhibited the behaviors or characteristics. This scale was created only if there were valid data on at least 4 of the 6 items. The score was computed as the mean of the items comprising the score. For the fall of kindergarten, this measure has a reliability of .91.

Covariates. To reduce bias in the estimated effects of kindergarten school readiness skills on subsequent academic achievement, the current analyses also included controls for a diverse set of demographic characteristics, home and family resources, and parenting practices. The additional explanatory variables described below were collected from interviews with parents during the fall and spring of the kindergarten year. A complete list of the covariates and their summary statistics are provided in Table 1.

Child and parent characteristics. Covariates for children's demographic characteristics included: the child's race (non-Hispanic African American, Hispanic, Asian, or other, with non-Hispanic White as the reference group), gender (1=female), and age in years at the time of kindergarten testing. Variables for children's health were also included: birthweight in pounds, whether the child was prematurely born (1=premature), and a parent rating of overall child health. Geographic controls were also covariates in the analyses, including dummy variables for the locale (urban, suburban, and rural) and region (northeast, Midwest, south, west) of where the child resided. Parent characteristics were also included as controls, including: mother's age at first birth in years, mother's level of education, father's level of education, household income in thousands, mother's occupational prestige score, father's occupational prestige score, and if there was receipt of welfare in the last 12 months for WIC, food stamps, and TANF. The current analyses also included controls for educational expectations of the child as rated by parents, including the highest level of education the parent expected the child to complete and how important it was to the parent that the child is able to count, share, use a pencil or draw, pay attention and be calm, know letters, and express their needs and communicate well.

Home environment. Characteristics of the home environment were also included in the analyses, including the number of siblings, a dummy variable for whether the child was part of a multiple birth, the types of parental figures who lived with the child, whether English was the primary home language for the child (1=English is not primary home language), and whether the child moved four or more times in preschool. Controls for parental academic stimulation in the home included: the days per week that the parent read to the child, the days per week that the parent told stories to the child, and the number of books in the home. Controls for child care arrangements in preschool included dummy variables for whether the child had relative preschool care, non-relative preschool care, Head Start, other center-based preschool care, and whether the child was ever in center-based preschool care. Controls were also included for neighborhood characteristics, such as safety, drug use, and burglary, based on parent ratings.

Analysis Plan

We used ordinary least squares (OLS) regression to examine the relationship between EF and other kindergarten school-readiness skills and third grade reading and math achievement. In order to isolate the impact of EF on later achievement we controlled for an extensive set of prior child, family, and contextual influences that may have been related to children's achievement. We used Huber-White methods to adjust standard errors at the classroom-level to account for the lack of independence from the clustering of students.

In six separate models, we regressed children's third grade reading and math achievement on each of the three components of EF. We then ran three more models for each outcome: (1) a single regression with just the working memory and cognitive flexibility measures, (2) a single regression with all three measures of the EF components, and (3) a single regression that added in the full set of school readiness measures and background controls. All key variables of interest were standardized to have a mean of 0 and a standard deviation of 1 so that coefficients can be interpreted as effect sizes in standard deviation units. Sampling weights provided by the ECLS-K were applied to make all estimates nationally representative.

We accounted for missing data using the Full Information Maximum Likelihood (FIML) procedure in Stata 15.0 (Enders, 2001). FIML uses all available information within cases to estimate the missing parameters so that incomplete observations can be included to calculate estimates. The use of FIML relies on the assumption that data are missing at random, conditional on controlling for all other variables within the model. Some have suggested that FIML is equally as good and perhaps better than alternative methods, such as multiple imputation, for handling missing data (e.g., Allison, 2012a, 2012b).

Results

Descriptive statistics for all variables in the analysis are presented in Tables 1 and 2. All of the IRT test score averages increase substantially from the beginning to the end of kindergarten, and then by even larger increments to the end of first grade. Sample averages on teacher reports of problem behaviors, self-control, interpersonal skills, approaches to learning, and inhibitory control change relatively little over these grades. Averages on direct child assessments of working memory and cognitive flexibility increase slightly. Table 3 shows that the correlations among all measures of academic skills, social-emotional behaviors, and EF were all significant ($p<.001$) at the two time points of interest. Correlations between third grade test scores and school-entry EF measures ranged from .28 to .51. These correlations, in particular the high correlations between working memory and reading (r=.50) and math (r=.51), preview some of our regression results.

[INSERT TABLE 3]

Regression analyses were conducted to determine the extent to which EF components predicted children's long-run academic achievement to third grade. Tables 4 and 5 present estimates of our regression models relating EF to reading and math achievement, respectively. Despite our numerous control variables, we found no evidence of multicollinearity problems in our fully controlled regression models. Covariates were screened for multicollinearity using variance inflation factors (VIF), and all values were less than seven (a VIF score of 10 or higher typically denotes a problem with multicollinearity; see O'Brien, 2007). Additionally, the similarity of standard errors across our models suggests the absence of multicollinearity problems.

EF Components and Reading Achievement. Estimates from three bivariate regressions involving reading achievement for each of the core components of EF are presented in Model 1 of Table 4. The coefficient for working memory (B=.51, SE=.01, p<.001) translates into a half a standard deviation change in third-grade reading scores per standard deviation change in kindergarten-entry working memory, which is virtually identical to its counterpart .50 correlation shown in Table 3. The coefficients for inhibitory control (B=.33, SE=.01, p<.001) and cognitive flexibility (B=.32, SE=.01, p<.001) were about a third of a standard deviation. In Model 2, we estimated a single regression with both working memory and cognitive flexibility but not inhibitory control included as predictors because prior published studies (e.g., Little, 2017) using the EF measures of the ECLS-K 2011 dataset have argued that the teacher-reported measure of inhibitory control is inadequate. The regression results indicate that working memory was more predictive of reading achievement (B=.45, SE=.01, p<.001) than cognitive flexibility (B=.20, SE=.01, p<.001). In Model 3, we add in the inhibitory control measure to provide a more complete picture of the three EF components operating together to predict reading achievement. Working memory remains the most predictive (B=.41, SE=.01, p<.001), followed by inhibitory control (B=.21, SE=.01, p<.001), and then cognitive flexibility (B=.17, SE=.01, p<.001). Our final regression, presented in Model 4, adds in the other measures of school readiness and the full set of background controls. These controls decrease the magnitude of the coefficients of the EF components substantially. Although working memory remains the most predictive, its coefficient is reduced to about a fifth of a standard deviation (B=.18, SE=.01, p<.001). The coefficients for inhibitory control (B=.04, SE=.02, p<.01) and cognitive flexibility (B=.06, SE=.01, p<.001) also dropped substantially, in this case to below a tenth of a standard deviation. To compare the size of the coefficients for the different EF components, we conducted F-tests and found that the coefficient for working memory was significantly larger than the coefficient produced by inhibitory control (F=5.77, p<.05) and cognitive flexibility (F=5.62, p<.05). The coefficients on inhibitory control and cognitive flexibility were not significantly different from one another.

[INSERT TABLE 4]

EF Components and Math Achievement. Table 5 presents the estimates of the math achievement models. For the bivariate regressions in Model 1, we see similar coefficients as we did with the reading achievement estimates. The coefficient for working memory was the largest, at about half a standard deviation increase in math achievement per standard deviation (SD) increase in working memory (B=.52, SE=.01, p<.001), and the coefficients for inhibitory control (B=.28, SE=.01, p<.001) and cognitive flexibility (B=.35, SE=.01, p<.001) were about a third of a standard deviation. In Model 2, we see a similar pattern of results as we did for reading achievement. School-entry working memory predicted subsequent math achievement (B=.46, SE=.01, p<.001) better than cognitive flexibility (B=.22, SE=.01, p<.001). With the inhibitory control measure added in Model 3, we find that working memory is the strongest predictor of later math achievement (B=.43, SE=.01, p<.001), followed by cognitive flexibility (B=.20, SE=.01, p<.001), and inhibitory control (B=.15, SE=.01, p<.001). In the fully-controlled regression of Model 4, working memory is the strongest predictor of later math achievement (B=.18, SE=.01, p<.001), followed by cognitive flexibility (B=.08, SE=.01, p<.001), and inhibitory control (B=.02, SE=.01, p<.001). Although these coefficients are substantially smaller in magnitude compared with the uncontrolled models, the coefficients remain significantly predictive of third grade math achievement. The F-tests to compare the equality of the coefficients indicated that the coefficient for working memory was significantly larger than the coefficient produced by inhibitory control (F=4.95, p<.05) and cognitive flexibility (F=5.31, p<.05). Similar to the regression models for reading, the coefficients produced by inhibitory control and cognitive flexibility were not significantly different from one another.

Comparing EF Associations Across Reading and Math Achievement. We were also interested in comparing the coefficients for the core EF components across our models for the reading and math outcomes. We found that the coefficients on working memory were not statistically significantly different across the two outcome models. Inhibitory control (F=5.20, p<.05) was significantly larger for children's reading achievement and cognitive flexibility was significantly larger for children's math achievement (F=4.39, p<.05). However, we are cautious to make any comparisons of the size of the coefficients for inhibitory control and working memory beyond testing for statistically significant differences given that the effect sizes were less than a tenth of a standard deviation and perhaps substantively insignificant.

[INSERT TABLE 5]

Predictive Power of Other School Readiness Skills and Behaviors. Turning to coefficients on the school-entry measures of achievement, social-emotional behaviors, and learning-related behaviors in Model 4 of Tables 4 and 5, we see that school-entry reading (B=.22, SE=.01, p<.001) and math scores (B=.32, SE=.01, p<.001) are most highly predictive of subsequent reading achievement. School-entry math (B=.52, SE=.01, p<.001) was much more predictive of third-grade math achievement than were reading scores (B=.05, SE=.01, p<.001).

For the coefficients of the social-emotional behaviors, in no case are standard deviation increments associated with more than a .01 standard deviation increase in either reading or math achievement. Turning to the coefficients of the learning-related behaviors, we see that it is modestly predictive of both reading (B=.09, SE=.02, p<.001) and math (B=.11, SE=.02, p<.001) achievement and about as predictive of these two outcomes as cognitive flexibility.

Robustness Checks

We engage in extensive robustness checks to understand how the estimates in our preferred models hold up to alternative model specifications. Detailed results from these checks can be found in the Appendix.

Exclusion of Learning-related Behaviors. One concern of this study is that controls for learning-related behaviors might rob kindergarten-entry EF skills of some of their explanatory power, particularly in light of the high correlation ($r = .79$) between inhibitory control and learning-related behaviors. To address this, we ran full-control models excluding learning-related behaviors. Coefficients on the components of EF changed very little. With the learning-related behaviors excluded, working memory remains the most predictive EF component of reading (B=.18, SE=.01, p<.001) and math achievement (B=.18, SE=.01, p<.001). For reading achievement, cognitive flexibility remained just as predictive (B=.06, SE=.01, p<.001) and inhibitory control did as well (B=.08, SE=.01, p<.001), although the coefficient increased marginally. For math achievement, we observed a similar pattern with cognitive flexibility being just as predictive (B=.08, SE=.01, p<.001) with the exclusion of learning-related behaviors, and the coefficient on inhibitory control increased (B=.09, SE=.01, p<.001). With the exception of internalizing behaviors, which became statistically significant (reading: (B=.02, SE=.01, p<.001; math: B=.03, SE=.01, p<.001), none of the other social-emotional variables attained statistical significance.

Classroom Fixed Effects. Even our substantial number of control variables may not capture all of the important child, family and other contextual dimensions affecting EF and later school achievement. A particular concern is with teacher-reported cognitive flexibility because different teachers may impose different standards for judging the level of cognitive flexibility in students. To address this concern, as well as more general biases arising from the selection of children into schools and classrooms, we re-estimated our models with adjustments for kindergarten classroom fixed effects. By transforming dependent and independent variables into deviations from classroom-specific mean values, fixed effects models produce estimates that are based only on within-classroom variation. Another way of thinking about this adjustment is that it is equivalent to including a dummy variable indicator for each classroom. Because we could not estimate FIML versions of fixed effect models, we accounted for missing data with missing dummy variables.

We found that estimates from these fixed-effects models differed little from estimates in our main analysis model. Controlling for the kindergarten classroom that children were in, we found that working memory (B=.09, SE=.01, p<.001), followed by inhibitory control (B=.06, SE=.02, p<.001), and cognitive flexibility (B=.03, SE=.01, p<.05) were predictive of reading achievement. For math achievement, we found that working memory (B=.13, SE=.01, p<.001) was most predictive, followed by cognitive flexibility (B=.05, SE=.01, p<.001), and inhibitory control (B=.03, SE=.01, p<.05), controlling for classroom fixed effects.

Change Models. As a further check on the robustness of our results, we estimated models similar to those used in Claessens et al. (2009) in which third grade achievement is predicted by end-of-kindergarten measures (EF components in our case) controlling for beginning-of-kindergarten components. The logic of this change model is that if a skill or behavior affects long-term achievement, then short-term changes in that skill or behavior, controlling for their baseline values, ought to be predictive of subsequent achievement. Coefficients on these end of kindergarten measures can be interpreted as the effect of skill and behavior changes over the course of the kindergarten year. Results indicate that gains in EF skills over the kindergarten year are predictive of third grade reading and math achievement. Working memory (B=.05, SE=.01, p<.001) and inhibitory control (B=.03, SE=.01, p<.05) were found to be predictive of reading achievement, but not cognitive flexibility (B=.01, SE=.01, p>.05). For math achievement, working memory (B=.06, SE=.01, p<.001) and cognitive flexibility (B=.02, SE=.01, p<.05) were found to be predictive of reading achievement, but not inhibitory control (B=.01, SE=.02, p>.05). In contrast, none of the changes in behavior problems and social skills across kindergarten were significant predictors of later reading and math achievement.

Non-linearity. We also investigated possible nonlinear relations between the EF measures and later achievement. It may be the case that tasks aimed at measuring EF, such as the DCCS, are the product of early growth in cognitive control, producing a possible ceiling effect. If EF skills were only found to be predictive of later achievement because the highest-achieving children in kindergarten demonstrated proficiency on the EF measures, and these same children may be the highest achievers in third grade for reading and math achievement. We tested this assumption with a model with a second-order polynomial in which kindergarten EF components were included as quadratic terms. In the models predicting reading achievement, none of the coefficients on the quadratic terms for inhibitory control (B=.02, SE=.01, p>.05), working memory (B=.02, SE=.01, p>.05), and cognitive flexibility (B=-.02, SE=.01, p>.05) was statistically significant. In the models predicting math achievement, none of the coefficients on the quadratic terms for inhibitory control (B=.01, SE=.02, p>.05), working memory (B=.02, SE=.01, p>.05), and cognitive flexibility (B=-.00, SE=.00, p>.05) was statistically significant. In sum, these results suggest that the effect of a standard deviation gain on any of the EF measures on later achievement was similar for children at the bottom and top of the distribution.

Teacher-reported Outcomes. In light of the consistent predictive validity between teacher reports and children's future cognitive performance (e.g., Fuhs et al., 2015), we also estimated model in which teacher-reported math and reading achievement in third grade were regressed on our kindergarten-entry components of EF and controls. Coefficients on the components of EF were quite similar to those presented in Tables 4 and 5. For reading achievement, working memory is the strongest predictor of later math achievement (B=.14, SE=.01, p<.001), followed by cognitive flexibility (B=.07, SE=.02, p<.001), and inhibitory control (B=.04, SE=.01, p<.01). For math achievement, working memory is the strongest predictor of later math achievement (B=.17, SE=.01, p<.001), followed by cognitive flexibility (B=.10, SE=.01, p<.001), and inhibitory control (B=.02, SE=.01, p<.05).

Discussion

The goal of the current study was to use nationally-representative data to investigate the associations between EF subcomponents at school entry and end of third grade academic achievement in the context of models that control for a host of concurrent measures and to explore the robustness of results to important features of the data. Our findings indicate that the core EF components show somewhat different associations across domains of academic achievement at the end of third grade. Associations were strongest for working memory in predicting both reading and math achievement. The evidence for cross-domain links was weaker for inhibitory control and cognitive flexibility, with the effect sizes on reading and math achievement at less than a tenth of a standard deviation (.04 to .06 on reading, .02 to .08 on math) in our preferred model. Adding to the existing literature, we also conducted extensive robustness checks to ensure that our results are not sensitive to the set of decisions that led to the specification of our featured regression models.

A strength of our study is that the data enable us to relate influences of three core components of EF and a strong set of academic outcomes measured in the fall of the kindergarten year, as well as a set of teacher-rated dimensions of social-emotional and learning-related behaviors concurrently measured, to long-run academic outcomes measured at the end of third grade. By investigating the predictive strength of each kindergarten EF component in relation to one another, we can better understand the relative importance of each kindergarten competency for building longitudinal academic achievement.

Though the relations between EF components and math achievement have been more thoroughly documented than with reading achievement, our study suggests that EF skills are important for academic achievement more generally. That working memory was most predictive of both reading and math achievement, net of inhibitory control and cognitive flexibility, corroborates other studies that have observed similar patterns (Allan et al., 2014; Bull & Scerif, 2001; Geary, 2011; Welsh et al., 2010). Working memory may be most beneficial of the three EF components to reading and math achievement because of the increasing demand of complex thinking skills in the later grades. For example, working memory helps children to store and manipulate relevant information, which allows them to learn and recall complex arithmetic procedures to perform steps in the correct order. In reading, children need to monitor their comprehension in order to combine and remember multiple sources of information from texts in order to make inferences. Interestingly, Geary (2011) found differential relationships between working memory and academic achievement from kindergarten through fifth grade. The importance of working memory for reading decreased as children progressed through school but increased for math achievement and working memory with successive grades.

It is possible that there are multiple components of working memory that are uniquely predictive of academic achievement in addition to the classroom environment itself that becomes increasingly complex for children (Cuevas et al., 2012; Vandenbroucke et al., 2018). Though we are unable to unpack these mechanisms, future data from the ECLS-K 2011 will allow us to explore whether there are differential effects of working memory for reading and math achievement beyond third grade.

In prior studies that have examined the core EF components in school-age children, the finding is that either inhibition (Blair & Razza, 2007; Brock, Rimm-Kaufamn, Nathanson, & Grimm, 2009; Espy et al., 2004) or cognitive flexibility (van der Sluis, de Jong, & van der Leij, 2004; van der Sluis et al., 2007) is uniquely predictive of academic achievement. Several reasons may account for our different pattern of results. First, it may be the case that our third-grade measurement of academic outcomes is still relatively early in children's formal schooling. We might find that inhibitory control or cognitive flexibility will be more predictive of later than earlier reading and math outcomes as EF components develop at different rates (Huizinga, Dolan, & van der Molen, 2006). Data from the final wave of the ECLS-K 2011, when students are in fifth grade, will provide some information about this. Second, and what may be the larger issue, concerns the different measures used across the studies. This lack of standardization of EF measures across different studies examining the relations between EF academic achievement is a major problem for the field (see Morrison & Grammer, 2016 for a discussion), making it difficult to isolate the unique contributions of each EF component. Although results of this study provide information regarding the strength and direction of the relation between working memory and academic achievement, it remains an open question whether the observed effects of working memory remain when different tasks or measures are used.

Implications

With respect to early childhood interventions, the results of the present study cast doubt on the idea that scaled-up interventions targeting working memory or any of the other EF components would generate large long-run benefits to children's achievement. Even for the strongest correlate to emerge from our study – working memory – our preferred estimate of the association between a SD increase in working memory and later achievement is .18. Although highly significant in a statistical sense, it may be small in a practical sense because of the difficulties of promoting large, longer-run increases in working memory. The EF intervention literature shows much smaller increases. For example, the Tools of the Mind program evaluation of Blair and Raver (2014) showed .14 SD impacts on working memory at the end of treatment; no follow-up data were available to assess the persistence of these effects. But even if the .14 SD impact persisted, our .18 coefficient on working memory translates into a third-grade achievement gain of only about .03 SD.

There are some early childhood interventions that have been successful at improving children's EF, such as the Boston Pre-K program (Weiland & Yoshikawa, 2013). Though it was a high-quality preschool intervention that also directly targeted children's early math and literacy skills, it was also found to improve children's EF and academic achievement. It may be the case that EF interventions that would show the largest transfer to children's academic achievement would be those that affect the factors influencing all of children's EF skills, rather than a specific one (e.g., working memory; see Diamond, 2012). Perhaps early childhood interventions that also directly target children's academic skills, such as those that integrate EF training and academic instruction together, will produce the largest and longest lasting effects on both skills (Clements, Sarama, & Germeroth, 2016, make a similar argument). However, though interventions targeting children's EF components may be worthwhile to help children become independent, organized, and well-regulated thinkers and learners, it is not clear from this particular study that we should expect these efforts to produce strong longer-run gains on academic success. Much more work is needed to establish the size of causal connections between EF and achievement.

Current policy and program initiatives emphasize the potential of EF interventions in preparing children for school, however additional research is needed to establish the extent to which children participating in these types of early childhood interventions are gaining school readiness skills. Jacob and Parkinson (2015) find little indication of substantial increases in children's academic outcomes in methodologically-strong school-based EF intervention evaluations. The evidence base on these EF interventions is still mixed as there are few of these program evaluations that have assessed longitudinal impacts on children's achievement after they have transitioned to school, and future research will need to address the nature of influences across different academic domains over time.

Limitations

This study has a number of noteworthy limitations. First is that while our list of child, family, and contextual control variables is more extensive than in most developmental studies, they do not eliminate all concerns over bias. Most obvious is that, despite baseline controls for math and literacy achievement, we lack direct controls for children's cognitive ability. Given the links between working memory and IQ, failure to control for IQ risks attributing to potentially-malleable working memory what is really caused by less malleable IQ. With respect to the social-emotional behaviors included in this study, it may be the case that there are some sleeper effects and these behaviors may actually be predictive of later than earlier academic outcomes in elementary school.

Moreover, there are drawbacks to using a large-scale dataset to examine EF and its relations to longitudinal achievement. Although the large size of the ECLS-K 2011 dataset ensures a broad population-based view of the associations we estimate, the tradeoff is that the dataset includes neither multiple measures of the same EF components nor exhaustive measures that might be found in relatively smaller, locally focused studies. Since the ECLS-K 2011 provided only one measure for each EF subcomponent, it was not possible to examine multiple measures of each component of EF, but it should be a direction for future research. In any case, we are cautious to make any claims about which EF components are the "best" predictors of later academic achievement as their predictive validity is heavily dependent on measurement.

A related concern is that measures of EF in the broader research literature have been criticized for not capturing their targeted constructs. For example, our EF measures may also be capturing motor and verbal abilities (Welsh et al., 2010). The amount and nature of EF that are involved in a task vary greatly and no measure purely assesses the use of only one EF capacity (Diamond, 2006; Garon, Bryson, & Smith, 2008). Further, the measure of inhibitory control used in this study was a teacher report as opposed to a direct measure. Teacher ratings have often been criticized for introducing teacher bias or including limited information related to the context of the child's behavior or behavior intensity.

Other well-validated scales to assess children's EF, such as the Brief Rating Inventory of Executive Functions (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000) have shown modest convergent validity with direct assessments and have actually been found to contribute to predicting academic achievement over and above the direct assessments. Further, there is also debate over the degree to which direct assessments of children's EF are valid measures of the ways that these skills may manifest themselves in contexts such as the classroom or elsewhere (Isquith, Roth, & Gioia, 2013; Morrison, Ponitz, & McClleland, 2010; von Suchodoletz, Uka, & Larsen, 2015). Isquith et al. (2013) argue that both a combination of direct assessments and rating scales can provide a more comprehensive picture and additional information in capturing children's EF. Moving forward, researchers in the EF field will need to think carefully about the measurement of these important skills for children's long-run achievement. If feasible, researchers should consider using multiple measures, both direct assessments and reports from teachers and parents, for each key component of EF. Research on children's EF skills would also benefit from future studies that use several types of reading and math tasks that would demonstrate the role of EF in different types of academic learning.

It is important to note that measures of inhibitory control and learning-related behaviors are not definitive, but instead represent our operationalization of these multifaceted constructs based on the available measures we have in our data source. These two measures demonstrate overlap given that the inhibitory control measure was more strongly correlated with the learning-related behaviors measure than any of the others. Ignoring any and all similarity in the content of these two measures, it may be the case they are similar simply because they were reported by the same person (see Campbell & Fiske, 1959). We emphasize that when interpreting the strength of these associations, the different assessment methods must be taken into account. We encourage future studies to adopt multimethod approaches to examining children's EF and its development across both academic and non-academic domains to other important indicators of school readiness. It will be important to replicate the associations documented from the current study with other measures of EF and learning-related behaviors.

Finally, one substantial limitation to this study is that our models could be argued as being overcontrolled. Disentangling early EF skills from other school readiness skills that covary with EF skills is difficult, and causal inferences are not appropriate for the present study when associations between EF components and achievement have been estimated using nonexperimental data. Although our use of multiple covariates reduces the chance that the obtained associations can be explained by omitted variables, we may be controlling for and thus removing the very effects that we are interested in (Newcombe, 2003). It may be the case that the core EF components in our study are causally related to concurrently measured covariates and so the inclusion of such covariates actually leads to an underestimate of the effects of EF components on children's academic achievement. Although our goal in this study was to be as rigorous as possible in reducing bias in the associations of early EF and academic achievement, we encourage future research to examine their complex network of relations to more clearly establish causal connections before taking interventions to scale.

Conclusions

Although limited in some ways, this analysis of EF components in the elementary grades provides nationally-representative information about its relations with academic achievement during a key period in children's schooling. Our findings suggest that working memory is the EF component most predictive of later achievement, particularly for math. Evaluating a wide range of these kinds of skills across different domains during childhood may help schools forecast academic achievement in future grades. Although this study has provided some foundation for the predictive relations between EF components and long-run academic achievement, more research is clearly needed to establish whether improvements in EF lead to meaningful, consistent impacts and to inform whether intervening on one or more particular components of EF will boost children's long-run academic achievement.

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Table 1. Descriptive statistics for the study sample.

	Mean (SD)
Baseline Child Characteristics	
Race	
Black	.13 (.33)
Hispanic	.26 (.43)
Asian	.04 (.20)
Other	.05 (.23)
Female	.49 (.50)
Age (in months at fall K assessment)	67.54 (4.45)
Age (squared)	4581.32 (611.15)
Age (cubed x 1000)	3.12e+08 (6.34e+07)
Birthweight (in pounds)	6.85 (1.35)
Premature birth (over two weeks early)	.20 (.40)
Parent report of overall child health (1=excellent; 5=poor)	1.58 (.81)
Geographic Controls	
Urban	.41 (.49)
Suburban	.34 (.47)
Rural	.23 (.42)
Northeast	.14 (.35)
Midwest	.24 (.43)
South	.39 (.49)
West	.23 (.42)
Home Environment	
Siblings	1.49 (1.10)
Siblings (squared)	3.43 (5.51)
Siblings (cubed)	1.44 (37.61)
Child part of multiple birth	.04 (.18)
Two biological or adoptive parents	.66 (.47)
One biological or adoptive parent and one other parent	.06 (.23)
One biological or adoptive parent only	.17 (.38)
Other guardian(s)	.02 (.13)
English not primary home language	.15 (.35)
Four or more moves in preschool	.09 (.29)
Reads to child (days/week)	5.41 (1.95)
Tells stories to child (days/week)	4.60 (2.31)
Number of books in the home	91.95 (146.25)
Mother's age at first birth	24.62 (5.77)
Mother's Education	
Did not finish high school	.14 (.35)
High school graduate	.17 (.38)
Some college	.33 (.47)
Bachelor's degree or higher	.36 (.48)
Father's education	
Did not finish high school	.11 (.32)
High school graduate	.18 (.38)
Some college	.43 (.50)
Bachelor's degree or higher	.29 (.45)
Income	69155.35 (53985.05)
Mother's occupation (prestige score)	45.08 (1.12)
Mother's occupation (squared)	2134.72 (1006.52)
Mother's occupation (cubed x 1000)	1.06e+08 (7.85e+07)
Father's occupation (prestige score)	43.56 (9.78)
Father's occupation (squared)	1993.23 (979.03)
Father's occupation (cubed x 1000)	9.63e+07 (7.74e+07)
WIC in the last 12 months	.45 (.50)

Food stamps in the last 12 months	.25 (.43)
TANF in the last 12 months	.05 (.22)
Child Care Arrangements in Pre-K	
Relative pre-school care	.24 (.43)
Non-relative pre-school care	.11 (.31)
Head Start	.13 (.34)
Center-based pre-school care	.69 (.46)
Child ever in center-based pre-school care	.56 (.50)
Neighborhood Characteristics (1=Big problem; 3=No problem)	
Neighborhood safety	2.69 (.53)
Neighborhood drug use	2.86 (.42)
Neighborhood burglary	2.79 (.47)
Parental Expectations for Child at Baseline	
Level of Education Parent Expects Child to Complete	
Will not finish high school	.00 (.04)
High school graduate	.04 (.20)
Some college	.14 (.35)
Bachelor's degree	.48 (.50)
Advanced degree	.33 (.47)
How important is it that your child does the following by kindergarten? (1=Essential; 5= Not important)	
Count	2.03 (.82)
Share	1.64 (.59)
Use pencil/draw	1.88 (.73)
Pay attention/be calm	1.86 (.68)
Know letters	1.91 (.77)
Express needs/communicate well	1.61 (.57)
Observations	17300

Note. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. Weighted using ECLS-K sampling weights.

Table 2. Weighted Sample Summary Statistics of Key Independent and Dependent Variables.

	Mean (SD)	Reliability
Fall of Kindergarten		
Executive Functioning		
Inhibitory Control	4.93 (1.22)	.87
Working Memory	93.37 (16.52)	−
Cognitive Flexibility	14.25 (3.27)	−
Academic Skills		
Reading IRT Score	37.42 (9.55)	.95
Math IRT Score	3.41 (1.95)	.92
Oral language	18.37 (3.28)	.91
Socio-emotional Behaviors		
Externalizing Problem Behaviors	3.41 (.59)	.88
Internalizing Problem Behaviors	3.55 (.46)	.79
Self-control	3.09 (.57)	.81
Interpersonal Skills	3.00 (.59)	.86
Learning-related Behaviors	2.95 (.65)	.70
Spring of Kindergarten		
Executive Functioning		
Inhibitory Control	5.10 (1.23)	.87
Working Memory	95.25 (16.96)	−
Cognitive Flexibility	15.21 (2.74)	−
Academic Skills		
Reading IRT Score	49.70 (11.53)	.95
Math IRT Score	43.40 (11.46)	.94
Oral language	19.07	.89
Socio-emotional Behaviors		
Externalizing Problem Behaviors	3.38 (.60)	.89
Internalizing Problem Behaviors	3.50 (.47)	.78
Self-control	3.19 (.60)	.82
Interpersonal Skills	3.15 (.62)	.87
Learning-related Behaviors	3.11 (.66)	.72
Spring of Third Grade		
Academic Skills		
Reading IRT Score	11.09 (12.54)	.93
Math IRT Score	97.56 (14.43)	.93

Note. Unstandardized means. Standard deviation in parentheses. Weighted using ECLS-K sampling weights. "Reliability" column refers to reliabilities reported in the ECLS-K user's manual. For reliability of reading and math IRT-based scores, the reliability of the overall ability estimate, theta, was based on the variance of repeated estimates of theta compared with the total sample variance. All other reliabilities are Cronbach's alpha. Reliabilities for working memory and cognitive flexibility were not reported. Dashes indicate unavailable information.

Table 3. Correlation matrix for spring of third grade test scores and fall kindergarten test scores and teacher report measures.

	1	2	3	4	5	6	7	8	9	10	11	12	13
Fall of Kindergarten													
Executive Function													
1. Inhibitory Control	1												
2. Working Memory	.23	1											
3. Cognitive Flexibility	.18	.26	1										
Academic Skills													
4. Reading IRT Score	.28	.48	.27	1									
5. Math IRT Score	.31	.55	.34	.77	1								
6. Oral language	.12	.28	.29	.33	.36	1							
Social-emotional Behaviors													
7. Externalizing Problem Behaviors	.70	.15	.11	.15	.16	.03	1						
8. Internalizing Problem Behaviors	.20	.10	.06	.13	.14	.06	.26	1					
9. Self-control	.68	.17	.13	.19	.21	.11	.71	.26	1				
10. Interpersonal Skills	.64	.18	.15	.22	.24	.15	.59	.31	.79	1			
11. Learning-related behaviors	.79	.28	.20	.37	.40	.16	.59	.30	.71	.74	1		
Spring of Third Grade													
Academic Skills													
12. Reading IRT Score	.32	.50	.31	.55	.62	.35	.20	.12	.23	.26	.38	1	
13. Math IRT Score	.28	.51	.34	.51	.67	.30	.15	.12	.18	.20	.34	.73	1

Note. All correlations are statistically significant at $p<.001$.

Table 4. Regression models estimating spring of third grade reading achievement with fall of kindergarten executive function, academic outcomes, social-emotional behaviors, and learning-related behaviors.

	Model 1	Model 2	Model 3	Model 4
	Three bivariate regressions	Single regression of WM and CF measures	+ IC measure	+ Other school readiness measures and background controls
Executive Function				
Inhibitory Control	.33 (.01)***		.21 (.01)***	.04 (.02)**
Working Memory	.51 (.01)***	.45 (.01)***	.41 (.01)***	.18 (.01)***
Cognitive Flexibility	.32 (.01)***	.20 (.01)***	.17 (.01)***	.06 (.01)***
Academic Skills				
Reading IRT Score				.22 (.01)***
Math IRT Score				.32 (.01)***
Oral language				.13 (.01)***
Social-emotional Behaviors				
Externalizing Problem Behaviors				.00 (.01)
Internalizing Problem Behaviors				.02 (.01)***
Self-control				-.02 (.02)
Interpersonal Skills				.01 (.02)
Learning-related behaviors				.09 (.02)***
Background Controls	No	No	No	Yes
N	16950-17320	17320	17320	17320

Note. Standard errors in parentheses. Model 1 includes estimates from individual regressions. WM = working memory; CF = cognitive flexibility; IC = inhibitory control. All variables are standardized by full sample standard deviations. Control variables are listed in Table 1. Models are weighted using ECLS-K sampling weights. Externalizing and internalizing behavior problems and social skills were measured by teacher reports from the Social Skills Rating System. Learning-related behaviors were measured by the "Approaches to Learning" teacher report. Inhibitory control was measured by teacher reports. Working memory was measured with the Numbers Reversed Subtest from the Woodcock-Johnson III Tests of Cognitive Abilities. Cognitive flexibility was measured with the Dimensional Change Card Sort. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<.05; **p<.01; ***p<.001

Table 5. Regression models estimating spring of third grade math achievement with fall of kindergarten executive function, academic skills, social-emotional behaviors, and learning-related behaviors.

	Model 1	Model 2	Model 3	Model 4
	Three bivariate regressions	Single regression of WM and CF measures	+ IC measure	+ Other school readiness measures and background controls
Executive Function				
Inhibitory Control	.28 (.01)***		.15 (.01)***	.02 (.01)***
Working Memory	.52 (.01)***	.46 (.01)***	.43 (.01)***	.18 (.01)***
Cognitive Flexibility	.35 (.01)***	.22 (.01)***	.20 (.01)***	.08 (.01)***
Academic Skills				
Reading IRT Score				.05 (.01)***
Math IRT Score				.52 (.01)***
Oral language				.09 (.01)***
Social-emotional Behaviors				
Externalizing Problem Behaviors				.00 (.01)
Internalizing Problem Behaviors				.03 (.01)***
Self-control				-.01 (.02)
Interpersonal Skills				.00 (.02)
Learning-related behaviors				.11 (.02)***
Background Controls	No	No	No	Yes
N	16950-17320	17320	17320	17320

Note. Standard errors in parentheses. Model 1 includes estimates from individual regressions. WM = working memory; CF = cognitive flexibility; IC = inhibitory control. All variables are standardized by full sample standard deviations. Control variables are listed in Table 1. Models are weighted using ECLS-K sampling weights. Externalizing and internalizing behavior problems and social skills were measured by teacher reports from the Social Skills Rating System. Learning-related behaviors were measured by the "Approaches to Learning" teacher report. Inhibitory control was measured by teacher reports. Working memory was measured with the Numbers Reversed Subtest from the Woodcock-Johnson III Tests of Cognitive Abilities. Cognitive flexibility was measured with the Dimensional Change Card Sort. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<.05; **p<.01; ***p<.001

Supplemental Materials

Kindergarten Components of Executive Functions and Third Grade Achievement:
A National Study

Content:

Table A1. Regression models estimating spring of third grade reading and math achievement with fall of kindergarten school readiness skills excluding learning-related behaviors.

	Reading	Math
Executive Function		
Inhibitory Control	0.096***	0.076***
	(0.015)	(0.017)
Working Memory	0.097***	0.129***
	(0.012)	(0.012)
Cognitive Flexibility	0.035*	0.059***
	(0.013)	(0.014)
Academic Skills		
Reading IRT Score	0.272***	0.048*
	(0.015)	(0.016)
Math IRT Score	0.328***	0.563***
	(0.016)	(0.019)
Oral Language	0.150***	0.123***
	(0.011)	(0.012)
Social-emotional Behaviors		
Externalizing Problem Behaviors	-0.009	-0.011
	(0.018)	(0.017)
Internalizing Problem Behaviors	0.024*	0.026*
	(0.010)	(0.011)
Self-control	-0.014	-0.012
	(0.014)	(0.018)
Interpersonal Skills	0.014	0.025
	(0.017)	(0.019)
Observations	17320	17320

Note. Standard errors in parentheses. All variables are standardized by full sample standard deviations. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<0.05; **p<0.01; ***p<0.001

Table A2. Classroom fixed effects regression models estimating spring of third grade reading and math achievement with fall of kindergarten school readiness skills.

	Reading	Math
Executive Function		
Inhibitory Control	0.057***	0.032*
	(0.017)	(0.010)
Working Memory	0.093***	0.128***
	(0.013)	(0.013)
Cognitive Flexibility	0.028*	0.052***
	(0.013)	(0.013)
Academic Skills		
Reading IRT Score	0.256***	0.040**
	(0.015)	(0.015)
Math IRT Score	0.327***	0.548***
	(0.017)	(0.020)
Oral Language	0.160***	0.147***
	(0.019)	(0.011)
Social-emotional Behaviors		
Externalizing Problem Behaviors	-0.007	-0.008
	(0.018)	(0.017)
Internalizing Problem Behaviors	0.019	0.016
	(0.011)	(0.011)
Self-control		
Interpersonal Skills	-0.012	-0.004
	(0.019)	(0.019)
Learning-related Behaviors	0.097***	0.109***
	(0.021)	(0.019)
Observations	16700	16700

Note. Standard errors in parentheses. All variables are standardized by full sample standard deviations. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<0.05; **p<0.01; ***p<0.001

Table A3. Change models estimating spring of third grade reading and math achievement with spring of kindergarten school readiness skills controlling for fall of kindergarten skills.

	Reading	Math
Spring of Kindergarten		
Executive Function		
Inhibitory Control	0.033*	0.009
	(0.014)	(0.017)
Working Memory	0.054***	0.061***
	(0.012)	(0.012)
Cognitive Flexibility	-0.009	0.023*
	(0.012)	(0.011)
Academic Skills		
Reading IRT Score	0.489***	0.166*
	(0.020)	(0.020)
Math IRT Score	0.175***	0.502***
	(0.020)	(0.016)
Oral Language	0.153***	0.162***
	(0.017)	(0.016)
Social-emotional Behaviors		
Externalizing Problem Behaviors	-0.012	-0.033
	(0.018)	(0.017)
Internalizing Problem Behaviors	0.010	0.009
	(0.010)	(0.011)
Self-control	0.009	0.010
	(0.010)	(0.011)
Interpersonal Skills	-0.003	-0.007
	(0.019)	(0.018)
Learning-related Behaviors	0.132***	0.109***
	(0.020)	(0.020)
Fall of Kindergarten		
Executive Function		
Inhibitory Control	0.002	-0.001
	(0.018)	(0.019)
Working Memory	0.024*	0.045***
	(0.010)	(0.013)
Cognitive Flexibility	0.013	0.027*
	(0.012)	(0.011)
Academic Skills		
Reading IRT Score	0.142***	0.163***
	(0.017)	(0.017)
Math IRT Score	0.084***	0.190***
	(0.020)	(0.017)
Oral Language	0.095***	0.013***
	(0.014)	(0.014)
Social-emotional Behaviors		
Externalizing Problem Behaviors	0.001	0.011
	(0.019)	(0.014)
Internalizing Problem Behaviors	0.005	-0.001
	(0.011)	(0.010)
Self-control	0.001	0.021
	(0.022)	(0.016)
Interpersonal Skills	0.005	0.014
	(0.018)	(0.015)
Learning-related Behaviors	0.005	0.023
	(0.022)	(0.016)
Observations	17000	17000

Note. Standard errors in parentheses. All variables are standardized by full sample standard deviations. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<0.05; **p<0.01; ***p<0.001

Table A4. Non-linear regression models estimating spring of third grade teacher-reported reading and math achievement with fall of kindergarten school readiness skills.

	Reading	Math
Executive Function		
Inhibitory Control	0.040*	0.033***
	(0.016)	(0.008)
Inhibitory Control-squared	0.018	0.012
	(0.012)	(0.015)
Working Memory	0.19***	0.20***
	(0.010)	(0.012)
Working Memory-squared	0.023	0.027
	(0.014)	(0.016)
Cognitive Flexibility	0.083***	0.080***
	(0.014)	(0.013)
Cognitive Flexibility-squared	0.017	0.002
	(0.014)	(0.001)
Academic Skills		
Reading IRT Score	0.295***	0.063***
	(0.010)	(0.010)
Math IRT Score	0.313***	0.516***
	(0.011)	(0.012)
Oral Language	0.040**	0.043**
	(0.012)	(0.012)
Social-emotional Behaviors		
Externalizing Problem Behaviors	0.020	-0.001
	(0.014)	(0.014)
Internalizing Problem Behaviors	0.012	-0.023
	(0.010)	(0.014)
Self-control	-0.016	-0.011
	(0.016)	(0.015)
Interpersonal Skills	0.001	-0.023
	(0.014)	(0.014)
Learning-related Behaviors	0.083***	0.072***
	(0.016)	(0.016)
Observations	17320	17320

Note. Standard errors in parentheses. All variables are standardized by full sample standard deviations. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<0.05; **p<0.01; ***p<0.001

Table A5. Regression models estimating spring of third grade teacher-reported reading and math achievement with fall of kindergarten school readiness skills.

	Reading	Math
Executive Function		
Inhibitory Control	0.040**	0.022*
	(0.014)	(0.010)
Working Memory	0.143***	0.167***
	(0.006)	(0.005)
Cognitive Flexibility	0.073***	0.095***
	(0.017)	(0.011)
Academic Skills		
Reading IRT Score	0.419***	0.072***
	(0.013)	(0.020)
Math IRT Score	0.290***	0.537***
	(0.019)	(0.019)
Oral Language	0.164***	0.172***
	(0.016)	(0.015)
Social-emotional Behaviors		
Externalizing Problem Behaviors	0.001	0.014
	(0.012)	(0.015)
Internalizing Problem Behaviors	0.003	0.011
	(0.008)	(0.010)
Self-control	-0.014	-0.012
	(0.014)	(0.018)
Interpersonal Skills	0.012	0.009
	(0.007)	(0.011)
Learning-related Behaviors	0.126***	0.150***
	(0.011)	(0.018)
Observations	16750	16750

Note. Standard errors in parentheses. All variables are standardized by full sample standard deviations. Per IES/NCES guidelines, all sample sizes have been rounded to the nearest 10. *p<0.05; **p<0.01; ***p<0.001