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Foundations of mathematics and literacy: The role of executive functioning components

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ABSTRACT

The current study investigated the relations between the three cognitive processes that comprise executive functioning (EF)—response inhibition, working memory, and cognitive flexibility—and individual components of mathematics and literacy skills in preschool children. Participants were 125 preschool children ranging in age from 3.12 to 5.26 years ($M = 4.17$ years, $SD = 0.58$). Approximately 53.2% were female, and the sample was predominantly Caucasian (69.8%). Results suggest that the components of EF may be differentially related to the specific components of early mathematics and literacy. For mathematics, response inhibition was broadly related to most components. Working memory was related to more advanced mathematics skills that involve comparison or combination of numbers and quantities. Cognitive flexibility was related to more conceptual or abstract mathematics skills. For early literacy, response inhibition and cognitive flexibility were related to print knowledge, and working memory was related only to phonological awareness. None of the EF components was related to vocabulary. These findings provide initial evidence for better understanding the ways in which EF components and academic skills are related and measured. Furthermore, the findings provide a foundation for further study of the components of each domain using a broader and more diverse array of measures.

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Introduction

During the preschool years, children undergo rapid changes in their cognitive and academic functioning (Diamond, 2002; Ginsburg, Klein, & Starkey, 1998; Zelazo & Carlson, 2012). Executive functioning (EF), early mathematics, and emergent literacy have been identified as important precursors for academic success (Duncan et al., 2007) and, thus, are core aspects of school readiness. Successful acquisition of these skills, and the sub-skills within each of these domains, has long-lasting positive relations with later achievement and career success (Moffitt et al., 2011; National Early Literacy Panel [NELP], 2008; National Mathematics Advisory Panel [NMAP], 2008). These domains are related to, and predictive of, one another (Fuhs, Nesbitt, Farran, & Dong, 2014); most notably, children's early EF skills have been shown to support their acquisition of mathematics and literacy skills (Schmitt, McClelland, Tominey, & Acock, 2015; Tominey & McClelland, 2011).

Typically, relations between EF and academic domains are examined at a broad level (Bull, Espy, Wiebe, Sheffield, & Nelson, 2011; Fuhs et al., 2014; McClelland et al., 2007). Yet, these domains are each conceptualized as having distinct, but related, components (Lonigan, Burgess, & Anthony, 2000; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Purpura & Lonigan, 2013) that vary in their complexity and cognitive requirements; thus, the distinct constructs within each domain may be differentially related to the constructs in the other domains. The central focus of this study was to investigate the relations among EF, mathematics, and literacy skills at a relatively fine-grained level by focusing on the individual components of each construct.

Development of school readiness skills

Executive functioning

EF is generally defined as the adaptive, goal-directed control of thoughts, behaviors, and emotions (Best & Miller, 2010). It has also been identified as a higher level cognitive system that integrates and controls skills from more basic levels such as processing speed and memory span (Demetriou, Mouyi, & Spanoudis, 2010). EF is currently conceptualized as being composed of three related, yet distinct, cognitive processes that enable individuals to exert better control over information processing and behaviors: response inhibition (RI), working memory (WM), and cognitive flexibility (CF) (Miyake et al., 2000). RI refers to the ability to override a dominant or prepotent response in favor of a more adaptive one (Dowsett & Livesey, 2000). WM involves the simultaneous maintenance and manipulation of information (Gathercole, Pickering, Knight, & Stegmann, 2004). Finally, CF includes maintaining focus and flexibly adapting to changing goals or stimuli (Rueda, Posner, & Rothbart, 2005). There are two broad theoretical perspectives for the dimensionality of EF, both of which have empirical support (Garon, Bryson, & Smith, 2008). The first is that EF is a unitary construct (Hughes, Ensor, Wilson, & Graham, 2010; Wiebe, Espy, & Charak, 2008), and the second is that it is multidimensional in structure (Lerner & Lonigan, 2014; Lonigan, Lerner, Goodrich, Farrington, & Allan, 2016; van der Ven, Kroesbergen, Boom, & Leseman, 2013). Based on recent evidence that the components of EF may be dissociable (Lonigan et al., 2016; Miller, Geisbrecht, Müller, McInerney, & Kerns, 2012) and differentially predict academic outcomes (McClelland et al., 2014), we explored the three components of EF as unique predictors of academic skills.

Although EF develops across the life span, the preschool years are often thought of as a sensitive period for EF development because of rapid changes in the prefrontal cortex between the ages of 2 and 5 years (Zelazo & Müller, 2011). The cognitive complexity and control (CCC) theory (Frye, Zelazo, & Burack, 1998) is often used as a framework for understanding the development of EF. In this theory, it is posited that age-related changes in EF occur during developmental transitions in early childhood through a process that includes increases in cognitive and behavioral control through the acquisition of more complex rule systems (Zelazo, Müller, Frye, & Marcovitch, 2003). The acquisition of more complex rule systems likely allows for the development of more complex EF skills and, thus, potentially the use of these EF skills to support development in other areas.

Although there is scant evidence regarding the developmental progressions of the three EF skills (with the exception of clear linear growth during childhood), theoretical perspectives suggest that

RI and WM may develop first, laying the foundation for CF (Best & Miller, 2010; Diamond, Kirkham, & Amso, 2002; Garon et al., 2008). WM is thought to develop together with RI; however, unlike RI, which primarily develops during the preschool years, the trajectory of WM development starts in preschool but shows linear growth into adolescence (Best & Miller, 2010). RI and WM are thought to be prerequisites for the development of CF, suggesting that CF may be the most complex of the EF components. Indeed, for a child to effectively shift between tasks or sets of rules (CF), he or she must be able to inhibit previous instructions or rules (RI) and simultaneously maintain and manipulate new information (WM).

Mathematics

Prior to school entry, children begin to acquire early mathematics skills that form the basis for more advanced skills (NMAP, 2008). Early mathematics skills develop as a progression of highly related, but distinct, sub-skills (Baroody, 2003; Purpura, Baroody, & Lonigan, 2013) known as a learning trajectory (Sarama & Clements, 2009). Early numeracy skills are believed to develop during three overlapping phases, with each phase being more cognitively complex (Krajewski & Schneider, 2009). First, children learn to recognize small sets without counting (subitizing), distinguish between small quantities (set comparison), and learn the verbal counting sequence. Second, children apply the counting sequence to fixed sets (one-to-one counting) and make links between each of the number words and its respective quantity (e.g., apply cardinal number knowledge). Third, children combine number words and quantities into new number words and quantities without using physical objects (e.g., story problems). Furthermore, some preschool children can even reliably respond to basic formal addition combinations. These early skills, coupled with written symbolic-based skills (e.g., numeral naming, connecting quantities with numerals, comparing numerals, knowing the order of numerals), lay a foundation for the acquisition of more advanced skills such as addition with Arabic numerals (Purpura et al., 2013).

Literacy

A substantial body of research highlights the importance of the preschool years for the development of emergent literacy (e.g., Whitehurst & Lonigan, 1998). There are three components of emergent literacy: print knowledge, oral language, and phonological awareness (NELP, 2008). Print knowledge is a child's awareness of the basic conventions of print such as how to use books, the directionality of print, and letter names and sounds (Justice & Ezell, 2002). Oral language skills include word knowledge, vocabulary, understanding of word order, and knowledge of grammatical rules (Storch & Whitehurst, 2002). Phonological awareness is the ability to detect and manipulate language through such tasks as matching, blending, and deleting parts of words (Wagner & Torgesen, 1987). Combined, these three domains form the foundation for early reading and have been shown to have independent causal impacts on children's later reading skills (Whitehurst & Lonigan, 1998).

Importance of EF for academic skills

EF is often conceptualized as foundational for the development of school readiness domains, including mathematics and literacy (Blair & Razza, 2007; McClelland & Cameron, 2012). Within the context of early childhood classrooms, children must be able to pay attention, persist during challenging tasks, and avoid distractions in order to benefit from learning opportunities (McClelland, Geldhof, Cameron, & Wanless, 2015). Individual differences in early EF skills significantly predict both mathematics and literacy performance (Fuhs et al., 2014; McClelland et al., 2007) although this relation appears to be stronger and more consistent for mathematics than for literacy (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Blair & Razza, 2007; Willoughby, Blair, Wirth, & Greenberg, 2012).

Specific mathematics and literacy skills vary in complexity; thus, the development of these skills likely places different demands on the different EF components. For example, if RI is considered among the least complex of the EF components and develops primarily during the preschool years, it is likely recruited to support the acquisition of more basic mathematics (e.g., counting) and literacy (e.g., print knowledge) skills. WM may be a more complex EF skill because it continues to develop into adolescence and, thus, may be needed for the development of more sophisticated mathematics (e.g., calculation) and literacy (e.g., phonological awareness) skills. Furthermore, with CF potentially being the most complex domain, and enabling individuals to shift between rule sets, it may be related to more complex or more abstract mathematics and literacy concepts that require shifts in an individual's thinking (e.g., applying abstract concepts of quantity or print-related skills).

Response inhibition

In general, for mathematics, results are relatively consistent across studies in preschool; RI is a strong predictor of mathematics, even after statistically accounting for important covariates, including child age, child verbal and/or general intelligence, and maternal education (Blair & Razza, 2007; Espy et al., 2004). Few studies, however, have examined the role of RI in predicting different components of early mathematics (i.e., counting and calculation). Results from one study suggest that RI uniquely predicts the more basic skill of counting but not the more cognitively demanding task of calculation (Lan, Legare, Cameron Ponitz, Su, & Morrison, 2011), suggesting that RI may be distinctly related to different components of mathematics. However, there are several other components of mathematics that have not been explored in previous research.

Whereas the significant relation between RI and mathematics is generally consistent across studies, the association between RI and literacy is less clear. For example, in some studies, RI is an important predictor of aspects of literacy (Allan & Lonigan, 2011; Blair & Razza, 2007; Cameron et al., 2012); however, in other studies, RI and literacy are not significantly related (Davidse, de Jong, Bus, Huijbregts, & Swaab, 2011; Lan et al., 2011; McClelland et al., 2014). Notably, Cameron and colleagues (2012) found that RI predicted both print-related skills and vocabulary in young children. In contrast, McClelland and colleagues (2014) found no significant association between RI and letter decoding or vocabulary. Furthermore, Allan and Lonigan (2011) found that RI was more strongly related to both print knowledge and phonological awareness than it was to vocabulary, although it still was significantly related to vocabulary.

Working memory

Similar to RI, a substantial body of evidence has shown that WM is a significant predictor of achievement (Raghubar, Barnes, & Hecht, 2010; Savage, Lavers, & Pillay, 2007). As the demands of early mathematics and literacy skills become more complex (i.e., connecting quantities to form new quantities or connecting sounds to create words), WM requirements increase (Carretti, Borella, Cornoldi, & De Beni, 2009; Geary, Hoard, & Nugent, 2012). For example, in mathematics, WM is related to complex problem solving but not procedural skills (Fuchs et al., 2005). Furthermore, verbal WM is related to the components of early mathematics that require multiple steps or maintaining information in memory (e.g., calculation, number order) but not more basic components (e.g., verbal counting, one-to-one correspondence; Lan et al., 2011; Purpura & Ganley, 2014).

In terms of literacy skills, WM has been found to be predictive of change across the preschool years in vocabulary but not print-related skills (McClelland et al., 2014). Furthermore, WM has been found to be so highly related with phonological awareness that it has been found to load with phonological awareness skills in a test of the factor structure of phonological processing skills (Lonigan et al., 2009).

Cognitive flexibility

Relative to the other components of EF, CF has received less attention in the literature as a unique predictor of academic outcomes in preschool children. This could partially be explained by a lag in the development of assessments that are designed to tap CF at this age. For example, what is now a commonly used measure of CF for young children, the Dimensional Change Card Sort task (DCCS; Zelazo, 2006), has often been thought of as a complex inhibition task (Best & Miller, 2010) because it required children to shift between just two dimensions. Advances have since been made to the DCCS to increase its complexity (adding a third dimension), and many scholars now categorize it as a CF task (Garon et al., 2008).

Although some studies have documented a link between CF and academic performance (age 7 years and older; Bull, Johnston, & Roy, 1999; Bull & Scerif, 2001; Dobbs, Doctoroff, Fisher, & Arnold, 2006; McLean & Hitch, 1999; van der Sluis, de Jong, & van der Leij, 2004), findings are mixed—particularly for literacy—regarding the extent to which CF plays a role in the development of young children's academic skills. For mathematics, Lan and colleagues (2011) found that CF was related to both early counting and calculation skills. For literacy, some studies have found that CF is associated with vocabulary (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; McClelland et al., 2014), letter decoding (Dobbs et al., 2006; Lan et al., 2011), and print knowledge (Bierman et al., 2008). However, other studies have not documented similar relations, at least not for letter decoding (e.g., McClelland et al., 2014). Moreover, in some studies where CF is significantly correlated with mathematics and literacy, when other EF components (RI and/or WM) were controlled for, CF no longer predicted academic outcomes, suggesting that it might not have a unique relation with these outcomes (Blair & Razza, 2007; Espy et al., 2004; cf. Lan et al., 2011).

Limitations of prior work: a component analysis view

Despite the abundance of evidence connecting the components of EF individually to mathematics and literacy, the majority of studies examined the relations between only one or two components of EF and academic outcomes. Few studies have examined the relations between all three components of EF and mathematics and/or literacy in preschool (Espy et al., 2004; Lan et al., 2011; McClelland et al., 2014). In addition, the vast majority of studies connecting EF and academic outcomes use only broad measures of mathematics and literacy (e.g., the Woodcock–Johnson Applied Problems [WJ-AP] and Letter/Word ID [WJ-LWID] subtests). There is a limited body of evidence that has taken a componential approach to studying EF and either early mathematics (Kolkman, Kroesbergen, & Leseman, 2013; Lan et al., 2011) or emergent literacy (McClelland et al., 2014). Even these few studies were limited by the depth at which they conceptualized early mathematics and literacy. For example, in Lan and colleagues' (2011) study, early mathematics skills were defined as basic (counting) or complex (calculation). This categorization provides a strong foundation in separating out the components of mathematics, but there are numerous other components that constitute each of these categories and a number of other skills necessary for the acquisition of more formal skills (e.g., number knowledge) that were excluded. Even within counting, there are both procedural (verbal number sequence and one-to-one correspondence) and conceptual (cardinality) skills that may have different underlying cognitive requirements. Because both mathematics and literacy are composed of multiple components, and these components vary in their cognitive complexity, it is critical to understand how the different components of EF are uniquely related to each component of academic skills.

There is a need to comprehensively examine the unique relations of the components of EF with the components of mathematics and literacy for a number of reasons, including mixed evidence in prior research, narrow scope of prior work (e.g., connecting one component of EF to one component of math/literacy), and limited opportunities to synthesize patterns of relations across mathematics and literacy. Ultimately, understanding these nuanced relations—and using a breadth of EF, mathematics, and literacy measures to do so—may provide key insights into future research on assessment and intervention development.

The current study

The focus of the current study was to identify which components of EF are uniquely related to which components of mathematics and literacy in preschool while, at the same time, controlling for the other components of EF and key covariates. In this study, we used single measures of each construct of EF, mathematics, and literacy and acknowledge that use of singular measures of domains may result in issues of task impurity (Huizinga, Dolan, & van der Molen, 2006; Miyake et al., 2000). Task impurity refers to the notion that EF tasks likely tap more EF and non-EF processes than just the targeted EF component (e.g., RI). However, given the large number of tasks included in this study across all domains, it was not feasible to include more measures of EF due to time demands on children. Despite this issue, this study provides a starting point from which to build more targeted evaluations of these domains using a stronger depth of measurement for each construct.

Although there is mixed evidence about the relations between specific components of EF and mathematics and literacy outcomes, we have made some explicit hypotheses when warranted by consistency of evidence or theory and at other times have indicated an exploratory approach. Specifically, we hypothesized that:

(a) RI would be a predictor of basic mathematics skills, such as counting and cardinality, but not of more complex mathematics skills, such as calculation (as found in Lan et al., 2011), and RI would be significantly related to literacy skills, including print knowledge (as found in Allan & Lonigan, 2011; Cameron et al., 2012) and phonological awareness (as found in Allan & Lonigan, 2011; Blair & Razza, 2007). Because the evidence is mixed on the relation between RI and vocabulary, we take an exploratory approach to this research question.
(b) WM would be related to complex components of mathematics that require children to hold multiple pieces of information in mind (e.g., comparison) and combine or manipulate different pieces of information, such as calculation (as found in Lan et al., 2011; Purpura & Ganley, 2014), but not to basic mathematics skills, such as counting and cardinality (as found in Lan et al., 2011), and WM would also be related to vocabulary (as found in McClelland et al., 2014) and phonological awareness (as found in Lonigan et al., 2009) but not to print knowledge (as found in McClelland et al., 2014).
(c) Because there is limited evidence regarding the relation between CF and early mathematics and literacy skills, we approached these research questions in an exploratory manner. However, it is likely that CF will be related to more complex and abstract mathematics and literacy skills.

Method

Participants

Data were collected in 12 private preschools serving children from families with a range of socioeconomic backgrounds. Parents of 136 preschool children completed consent forms. Of those children, 4 left school before testing was completed and 7 did not assent to participate. The remaining 125 children were approximately evenly split by sex (53.2% female) and approximately representative of the demographics of the area (69.8% Caucasian, 12.7% multiracial, 8.7% Asian, 3.2% African American, 3.2% Hispanic, and 2.4% other race/ethnicity). Children were 3.12 to 5.26 years old (M = 4.17 years, SD = 0.58), were English speaking, and had no known developmental disorders. Of participating children, 25.6% had parents with a high school education or less, 32.0% had at least one parent with a college degree, and 42.4% had at least one parent with a postgraduate degree. This work was approved by the institutional review board.

Measures

Early numeracy

Twelve mathematics tasks were used to assess individual numeracy constructs from the different aspects of early mathematical knowledge noted earlier. Evidence of prior reliability and validity can be found from prior measure development (Purpura & Lonigan, 2015). For all tasks, children received 1 point for each correct response. All internal consistency scores were from the current study.

Subitizing. Children were briefly presented (2 s) with a set of pictures (set sizes from 1 to 7 presented in a linear fashion, e.g., ●●●●) and instructed to say how many dots or pictures were presented. There were a total of seven items (α = .57) on this task.

Set comparison. For each of the six items (α = .77), children were presented with four sets of dots on a page representing different quantities (e.g.,|●●●|●●|●●●●|●|). They were then asked which set had the most dots (three items) or fewest dots (three items).

Verbal counting. Children were asked to count as high as possible. When a child made a mistake, or correctly counted to 100 without making a mistake, the task was stopped. Self-corrections were not scored as incorrect. The highest number counted to was converted to a score based on a 7-point scale. Children were awarded 1 point each for correctly counting to 5, 10, 15, 20, 25, 40, and 100.

One-to-one counting. Children were presented with a set of 3, 6, 11, 14, or 16 dots on a page and asked to count the set (α = .80)

Cardinality (how many). This skill was assessed in the context of the one-to-one counting task. At the completion of the counting 3, 6, and 11 one-to-one counting items, children were asked to indicate how many dots there were in all (α = .84).

Cardinality (count a subset). There were a total of eight items (α = .83) for this task. In the first part of the task, children were presented with a specific quantity of objects (e.g., 15) and asked to count out ("give me *n*") a smaller set of objects (e.g., 4) from the larger set. Set sizes to be counted out were 3, 4, 8, and 16. In the second part, children were presented with pictures of both dogs and cars and instructed to count all of one type of picture (e.g., "count all the dogs"). Set sizes to be counted were 3, 8, 16, and 20.

Numeral identification. Children were presented with flashcards of nine numerals (1, 2, 3, 7, 8, 10, 12, 14, and 15) (α = .88) one at a time and asked, "What number is this?"

Set-to-numerals. This task had five items (α = .80). For the first three items, children were presented with a numeral at the top of the page (e.g., 3) and five sets of dots below (e.g.,|●●●●|●|●●●|●●|●●●●●|). They were instructed to identify which of the sets meant the same thing as the number at the top of the page. On the last two items, children were presented with a set of dots at the top of the page (e.g., ●●●●) and five numerals at the bottom (e.g., 4-2-3-1-5). They were instructed to identify which of the numerals meant the same thing as the set of dots at the top of the page.

Number order. This task had six items (α = .87). Children were shown a sequence of numbers with one number missing in between two numbers (e.g., 1 2 3 _ 5 6). They were asked what number comes before or after another number (e.g., "What number comes before 5?"). The items included identifying the numbers before 2, 5, and 15 and the numbers after 2, 9, and 15.

Number comparison. Children were asked to identify which of four numbers was the biggest or smallest. There were a total of six items (α = .76); three were presented visually with Arabic numerals and three were presented verbally.

Story problems. This task had seven items (α = .70). Children were presented verbally with story problems that did not contain distracters (e.g., irrelevant information). These story problems were simple addition problems (three items) or subtraction problems (four items) that were appealing to children. An example question was, "Johnny had one cookie and his mother gave him one more cookie, how many cookies does he have now?"

Formal addition. This task had five items (α = .58). Children were presented with a formal addition problem (e.g., 1 + 1 = ...) and asked, "How much is ...?"

Literacy

The Test of Preschool Early Literacy (TOPEL; Lonigan, Wagner, Torgesen, & Rashotte, 2007) was used to assess children's early literacy skills. This measure includes three subtests described below. The internal consistency scores for the TOPEL subtests are from the administration manual, and all measures have evidence of strong reliability and validity (Lonigan et al., 2007).

Print knowledge. This subtest measures print concepts, letter/word discrimination, letter name identification, and letter/sound identification. Children were asked to name or identify letters and letter sounds as well as concepts about print (e.g., identifying the front of a book). There are a total of 36 items ($\alpha = .95$) across three item sets that are either multiple choice or free response.

Definitional vocabulary. This subtest measures children's single-word spoken vocabulary and their ability to formulate definitions for words. There are a total of 35 items ($\alpha = .94$) for which children are asked to identify the picture (e.g., "What is this?") and describe its function (e.g., "What is it for?"). Children were awarded 1 point each for identifying and describing for a maximum of 70 total points.

Phonological awareness. This subtest includes both multiple-choice and free-response items involving blending and elision of words and sounds. For the blending tasks, children were asked to combine words or sounds together to create new words (e.g., "What do you get when you hear 'book' and 'bag' together?"). For the elision items, children were asked to separate sounds or words to create different words (e.g., "What do you get when you say "stack" without the /s/ sound?"). There are a total of 27 questions ($\alpha = .87$) divided into four sets (two blending and two elision).

Executive functioning

Three measures of EF that assess the primary EF components were used.

Response inhibition. A modified Stroop-like task was used to assess RI (Archibald & Kerns, 1999). Children were shown a page with pictures of suns and moons in a 5×6 layout. First, children were asked to say "moon" when they saw a picture of a moon and to say "sun" when they saw a picture of a sun. Children were timed to see how many pictures they could respond to correctly in 45 s. After children completed the first trial, they were asked to repeat the task, but this time they were told to say the opposite of the picture (i.e., "moon" for pictures of the sun and "sun" for pictures of the moon). In both trials, children were not allowed to continue on to the next picture until the previous picture was responded to correctly. When a child incorrectly responded, he or she was first asked, "What do you say for this one?" In the "opposite" trial, children were reminded that "This is the opposites game" if they continued to respond incorrectly. The final score used in this study was the number of items completed on the "opposite" trial in 45 s.

Verbal working memory. To assess WM, we used the computerized listening recall task from the Automated Working Memory Assessment (AWMA; Alloway, 2007). In this task, children listened to one or more sentences, were asked whether each sentence was true or false, and then were asked to recall the last word of each sentence in order. The task increased in difficulty after each set of questions (in the first set of questions children responded with the last word after one sentence, in the next set after two sentences, etc.). Children were explicitly informed that they would need to remember the last word(s). Children completed trials within each block until they did not recall any words from the sentences in the same block and were awarded 1 point for each correct last word they identified in the correct order. The outcome score was the total number of times a participant accurately recalled the last word in a sentence across trials. This test has been shown to have strong test–retest reliability ($r = .88$; Alloway, Gathercole, & Pickering, 2006).

Cognitive flexibility. A card sorting task based on the Three-Dimensional Change Card Sort (3 DCCS; Deak, 2003; McClelland et al., 2014; Zelazo, 2006; Zelazo et al., 2013) was administered to measure CF. During this task, children were asked to sort colored picture cards of a dog, fish, or bird on the basis of three dimensions: shape, color, and size. Four sorting boxes with model cards (either a dog, a fish, or a bird) affixed on them were placed directly in front of children. An additional box with a distracter card of a frog was also placed directly in front of children. Children were given one practice trial (sorting on the basis of shape) prior to testing trials. During all trials, children were given a card and asked, "Where does this one go?" and they were to place the card in one of the boxes. Reminders of the rules were not provided during testing trials. For the first six items, children were to sort on the basis of shape (e.g., the dog cards go in the sorting box with the dog card affixed). For the second six items, children were told that they were going to play a new game and would now sort on the basis of color. For the third six items, children were told that they were going to play a new game and would now sort on the basis of size. If children scored 5 or more points on the third section, a fourth set of items was administered with a new rule: When the card had a black border on it, children were to sort on the basis of size, and when the card did not have a black border, children were to sort on the basis of color. This same process and order was followed for all children. Therefore, the measure consists of either 18 or 24 items, with each sorting trial having 6 items. All items were weighted equally. Children were given a score of 0 for an incorrect response and 1 for a correct response, with scores ranging from 0 to 24. This measure has shown strong reliability (using tetrachoric correlations) in previous research (McClelland et al., 2014) and has a Cronbach's α of .94 in the current sample.

Covariates

A number of variables were included in each analysis as random- or fixed-effect covariates, including demographic variables and a measure of general cognitive ability.

Demographic variables. School was included in the model as a random-effect covariate to control for school-level effects. There were 12 schools with an average of 10.5 students per school. Three background variables were used as fixed-effects covariates in each analysis. These covariates were age, sex (male = 1, female = 0), and highest parental education (scored on an 8-point scale ranging from < eighth grade to doctoral/postgraduate degree).

General cognitive ability. Rapid automatized naming (RAN) was used to measure general cognitive ability. Although cognitive ability was not a primary variable of interest, it has been found to underlie academic skills (Georgiou, Tziraki, Manolitsis, & Fella, 2013) and is related to the processing component of the EF tasks because EF skills are higher order cognitive skills that control lower level cognitive skills such as processing speed (Demetriou et al., 2010). Thus, we included it as a fixed-effect covariate. RAN was assessed through a picture naming task and a color naming task. Children were asked to name four common pictures (e.g., house, cat, car, and pig). They were then presented with a page of 40 pictures (5×8) and asked to name the pictures in order as fast as they could. If a child incorrectly named a picture or skipped a picture, he or she was redirected back to that picture. The total time (in seconds) it took to name all 40 pictures was recorded. After the picture task, the same task was repeated but with colors (e.g., blue, red, green, and black). The average of the two completion times was used as the child's RAN score.

Procedure

Assessment procedure

Children were assessed on all tasks during the fall of the academic year in three or four 20- to 30-min sessions. Testing was conducted in shorter sessions as needed. Assessments took place in the local preschools at times identified by the schools in rooms/areas designated by the schools' directors/teachers. Individuals who either had completed or were working toward completion of a bachelor's degree in a social science field conducted the assessments. All testers completed two 2- to 3-h training sessions, followed by individual practice and a "testing-out" session to ensure that they were fluent with the assessment measures and general principles of working with children.

Analytic procedure

To evaluate the relations of EF with academic skills, separate mixed-effects regression analyses were conducted for each measure of mathematics and literacy as outcome variables. Covariates were included in all analyses. The three EF measures were included as fixed-effect predictors. z-scores were used for all regression analyses. To adjust for multiple comparisons and reduce Type I error, the Benjamini–Hochberg correction (Benjamini & Hochberg, 1995) was applied within each regression analysis. This correction adjusts the critical p-value in a stepwise manner based on the number of significance tests included within a particular set of analyses.

Results

Preliminary analyses

Means, standard deviations, ranges, skew, and kurtosis are presented in Table 1. All tasks were normally distributed. Zero-order and partial correlations accounting for age are presented in Table 2.

Primary analyses

Conditional intraclass correlation coefficients (ICCs) for all of the analyses were small (.01–.14), suggesting that there was little systematic variation at the school level. Results of each analysis are presented in Table 3 for mathematics and in Table 4 for literacy. In Table 5, a summary of the significance values for the three EF measures predicting each early mathematics and literacy outcome is presented.

Response inhibition

We hypothesized that RI would be related to more basic mathematics skills (e.g., counting, cardinality) and not with more complex mathematics skills (e.g., calculation). Results partially supported our hypothesis given that RI was related to mathematics skills more broadly than we anticipated. It was significantly related to many of the more basic mathematics measures, such as subitizing, verbal counting, one-to-one counting, cardinality (how many), and cardinality (count a subset), and was also related to some of the more complex mathematics skills (set-to-numerals, number order, and story problems). In regard to literacy skills, we hypothesized that RI would be related to both print knowledge and phonological awareness, which was partially supported because it was significantly related to print knowledge but not significantly related to phonological awareness. We examined RI's relation with vocabulary in an exploratory manner and found no relation.

Table 1
Means, standard deviations, ranges, skewness, and kurtosis of the sum scores of the mathematics, executive functioning, and processing measures.

Task	*Mean*	*SD*	*Range*	*Skew*	*Kurtosis*
Mathematics					
Subitizing	3.75	1.43	0–7	−0.22	0.17
Set comparison	3.25	1.84	0–6	−0.11	−0.94
Verbal counting sequence	2.77	2.02	0–7	0.25	−1.06
One-to-one correspondence	2.90	1.68	0–5	−0.12	−1.34
Cardinality (how many)	2.26	1.12	0–3	−1.11	−0.41
Cardinality (count a subset)	3.91	2.42	0–8	−0.02	−1.07
Numeral identification	5.09	2.81	0–9	−0.20	−1.06
Set-to-numerals	2.83	1.75	0–5	−0.24	−1.26
Number order	2.43	2.19	0–6	0.26	−1.40
Number comparison	1.84	1.84	0–6	0.96	−0.02
Story problems	2.57	1.96	0–7	0.60	−0.52
Formal addition	1.26	1.32	0–5	0.99	0.42
Literacy					
Definitional vocabulary	50.82	12.35	8–66	−1.32	1.44
Print knowledge	18.57	11.30	0–36	−0.10	−1.36
Phonological awareness	14.70	5.57	1–27	0.06	−0.55
Executive functioning					
Response inhibition	19.88	8.59	0–36	−0.28	−0.46
Cognitive flexibility	13.34	6.47	4–22	−0.01	−1.70
Verbal working memory	1.71	2.68	0–11	1.55	1.40
General cognitive ability					
Rapid automatized naming	79.71	30.47	37.50–186.89	1.39	1.98

Note. $N = 125$.

Table 2
Zero-order and partial correlations (accounting for age) between the sum scores of all tasks.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Mathematics																			
1. Subitizing	–	.32	.19	.33	.40	.36	.20	.30	.26	.08	.14	.21	.27	.26	.25	.33	.32	.23	−.16
2. Set comparison	.49	–	.29	.20	.33	.32	.14	.35	.35	.39	.24	.11	.29	.24	.19	.20	.28	.24	−.31
3. Verbal counting	.41	.48	–	.59	.45	.60	.49	.58	.54	.30	.46	.13	.59	.28	.32	.45	.35	.24	−.40
4. One-to-one counting	.48	.38	.68	–	.52	.74	.44	.64	.47	.28	.29	.18	.54	.22	.39	.52	.35	.16	−.38
5. Cardinality (how many)	.51	.44	.54	.59	–	.62	.51	.62	.50	.18	.38	.13	.57	.42	.24	.42	.53	.19	−.39
6. Cardinality (count a subset)	.51	.49	.69	.80	.67	–	.57	.67	.63	.38	.37	.27	.67	.26	.39	.41	.47	.20	−.47
7. Numeral identification	.37	.32	.58	.56	.58	.67	–	.56	.65	.26	.34	.32	.70	.11	.19	.29	.38	.14	−.34
8. Set-to-numerals	.46	.50	.67	.73	.67	.75	.66	–	.61	.28	.39	.14	.53	.17	.27	.43	.39	.11	−.43
9. Number order	.43	.50	.65	.60	.57	.72	.72	.71	–	.39	.45	.27	.63	.11	.26	.37	.41	.34	−.33
10. Number comparison	.31	.54	.47	.44	.32	.53	.42	.46	.54	–	.45	.25	.40	.16	.25	.24	.29	.30	−.24
11. Story problems	.30	.38	.55	.42	.46	.48	.45	.51	.55	.55	–	.23	.46	.31	.18	.41	.33	.26	−.19
12. Formal addition	.38	.31	.35	.33	.24	.41	.42	.31	.41	.40	.34	–	.29	.06	.13	.10	.19	.23	−.15
Literacy																			
13. Definitional vocabulary	.46	.45	.49	.43	.52	.47	.33	.40	.36	.39	.45	.30	–	.37	.30	.46	.47	.24	−.43
14. Print knowledge	.42	.43	.65	.63	.64	.74	.76	.63	.71	.52	.55	.39	.51	–	.30	.21	.18	.11	−.30
15. Phonological awareness	.39	.34	.43	.52	.35	.52	.35	.43	.42	.40	.31	.25	.45	.44	–	.23	.20	.26	−.19
Executive functioning																			
16. Response inhibition	.50	.41	.60	.62	.51	.55	.44	.57	.53	.43	.51	.30	.42	.56	.37	–	.35	.11	−.41
17. Cognitive flexibility	.46	.43	.48	.48	.60	.59	.50	.52	.54	.44	.44	.33	.38	.57	.35	.48	–	.12	−.34
18. Verbal working memory	.35	.37	.37	.29	.28	.33	.27	.26	.45	.41	.35	.34	.27	.35	.35	.26	.25	–	−.15
General cognitive ability																			
19. Rapid automatized Naming	−.32	−.44	−.52	−.49	−.47	−.57	−.45	−.53	−.46	−.39	−.31	−.31	−.46	−.51	−.31	−.52	−.45	−.26	–

Note. $N = 125$. All correlations except those underlined were significant at $p < .05$. Underlined correlations were nonsignificant. Correlations below the diagonal are zero-order correlations, and those above the diagonal are partial correlations accounting for age. RAN was scored with higher values (i.e. more time) indicating lower performance.

Table 3
Results of mixed effects regression analyses predicting the early numeracy measures.

	R^2	Standardized estimate	*SE*	*F*	*p*
Subitizing	.31				
Age		0.28	0.10	7.95	.006
Sex		−0.08	0.08	1.15	.287
Parent education		0.05	0.08	0.35	.558
Rapid automatized naming		0.05	0.09	0.36	.548
Response inhibition		0.25	0.10	6.65	.011
Cognitive flexibility		0.18	0.09	3.72	.056
Verbal working memory		0.15	0.08	3.66	.058
Set comparison	.29				
Age		0.32	0.10	10.05	.002
Sex		−0.10	0.08	1.69	.196
Parent education		0.07	0.08	0.63	.430
Rapid automatized naming		−0.19	0.09	4.16	.044
Response inhibition		0.03	0.10	0.09	.771
Cognitive flexibility		0.13	0.09	1.79	.183
Verbal working memory		0.16	0.08	3.89	.051
Verbal counting	.50				
Age		0.27	0.09	9.63	.002
Sex		−0.07	0.07	1.08	.302
Parent education		0.14	0.07	3.74	.060
Rapid automatized naming		−0.16	0.08	3.89	.051
Response inhibition		0.30	0.09	11.91	.001
Cognitive flexibility		0.08	0.08	1.06	.305
Verbal working memory		0.12	0.07	2.84	.095
One-to-one counting	.48				
Age		0.21	0.09	5.92	.017
Sex		−0.13	0.07	3.63	.059
Parent education		0.21	0.07	8.75	.004
Rapid automatized naming		−0.11	0.08	1.84	.177
Response inhibition		0.40	0.09	21.75	<.001
Cognitive flexibility		0.06	0.08	0.48	.488
Verbal working memory		0.03	0.07	0.14	.708
Cardinality (how many)	.38				
Age		0.00	0.09	0.00	.972
Sex		−0.05	0.07	0.48	.489
Parent education		0.16	0.08	4.42	.038
Rapid automatized naming		0.12	0.08	2.21	.140
Response inhibition		0.24	0.09	7.27	.008
Cognitive flexibility		0.34	0.09	15.54	<.001
Verbal working memory		0.07	0.07	0.78	.380
Cardinality (count a set)	.44				
Age		0.27	0.08	10.99	.001
Sex		−0.14	0.06	4.65	.033
Parent education		0.30	0.07	20.25	<.001
Rapid automatized naming		−0.21	0.07	8.24	.005
Response inhibition		0.18	0.08	5.07	.026
Cognitive flexibility		0.18	0.08	5.68	.019
Verbal working memory		0.04	0.06	0.38	.536
Numeral identification	.26				
Age		0.19	0.10	3.68	.058
Sex		0.05	0.08	0.43	.512
Parent education		0.19	0.09	5.10	.028
Rapid automatized naming		−0.14	0.09	2.34	.129
Response inhibition		0.14	0.10	2.21	.140
Cognitive flexibility		0.22	0.09	5.43	.022+
Verbal working memory		0.04	0.08	0.26	.610

Table 3 (*continued*)

	R^2	Standardized estimate	*SE*	*F*	*p*
Set-to-numerals	.37				
Age		0.22	0.09	5.80	.018
Sex		0.01	0.07	0.01	.920
Parent education		0.15	0.07	4.18	.043
Rapid automatized naming		−0.20	0.08	5.72	.018
Response inhibition		0.27	0.09	9.26	.003
Cognitive flexibility		0.16	0.09	3.45	.066
Verbal working memory		0.00	0.07	0.00	.992
Number order	.36				
Age		0.23	0.09	7.34	.008
Sex		−0.01	0.07	0.04	.849
Parent education		0.26	0.07	12.56	.001
Rapid automatized naming		0.05	0.08	0.45	.504
Response inhibition		0.23	0.08	7.29	.008
Cognitive flexibility		0.16	0.08	4.09	.045
Verbal working memory		0.21	0.07	9.22	.003
Number comparison	.33				
Age		0.31	0.10	10.19	.002
Sex		−0.12	0.08	2.54	.114
Parent education		0.06	0.09	0.42	.521
Rapid automatized naming		−0.07	0.09	0.70	.406
Response inhibition		0.10	0.10	1.01	.318
Cognitive flexibility		0.13	0.09	1.81	.181
Verbal working memory		0.23	0.08	8.13	.005
Story problems	.27				
Age		0.08	0.10	0.65	.422
Sex		0.00	0.08	0.01	.981
Parent education		0.06	0.09	0.52	.473
Rapid automatized naming		0.06	0.09	0.47	.495
Response inhibition		0.37	0.10	14.20	<.001
Cognitive flexibility		0.17	0.10	3.30	.072
Verbal working memory		0.19	0.08	5.30	.023
Formal Addition	.22				
Age		0.39	0.10	13.35	<.001
Sex		−0.19	0.08	5.33	.023
Parent education		0.03	0.09	0.11	.740
Rapid automatized naming		−0.09	0.10	0.91	.342
Response inhibition		−0.06	0.10	0.32	.574
Cognitive flexibility		0.10	0.10	0.99	.322
Verbal working memory		0.17	0.09	4.13	.045[+]

Note. $N = 125$. Sex was scored as male = 1 and female = 0. RAN was scored with higher values (i.e. more time) indicating lower performance.

[+] No longer significant after the Benjamini–Hochberg correction was applied.

Verbal working memory

We predicted that WM would be related to complex components of mathematics that require children to hold multiple pieces of information in mind (e.g., comparison) and combine or manipulate different pieces of information, such as calculation, but not to basic mathematics skills, such as counting and cardinality. In support of this hypothesis, our results showed that WM appeared to be significantly related to a narrow range of mathematics skills—specifically to those that required manipulation of quantities or the number sequence. It was significantly related to 3 of the 12 measures of mathematics (number order, number comparison, and story problems) and marginally significantly related to formal addition skills. Regarding literacy skills, we had predicted that WM would be related to both vocabulary and phonological awareness, but we found that it was significantly related only to phonological awareness. We had predicted that WM would not be related to print knowledge, and our results supported this hypothesis.

Table 4
Results of mixed effects regression analyses predicting the early literacy measures.

	R^2	Estimate	*SE*	*F*	*p*
Definitional vocabulary	.48				
Age		0.45	0.10	20.91	<.001
Sex		−0.11	0.08	1.95	.165
Parent education		0.07	0.08	0.81	.370
Rapid automatized naming		−0.22	0.09	6.01	.016
Response inhibition		0.05	0.10	0.27	.607
Cognitive flexibility		0.02	0.09	0.04	.835
Verbal working memory		0.03	0.08	0.17	.678
Print knowledge	.37				
Age		0.12	0.08	1.94	.167
Sex		−0.07	0.07	1.15	.285
Parent education		0.28	0.08	13.44	<.001
Rapid automatized naming		−0.14	0.08	3.51	.064
Response inhibition		0.29	0.08	12.82	.001
Cognitive flexibility		0.20	0.08	6.68	.011
Verbal working memory		0.09	0.07	1.90	.171
Phonological awareness	.30				
Age		0.17	0.10	2.67	.105
Sex		−0.05	0.08	0.36	.550
Parent education		0.00	0.10	0.00	.991
Rapid automatized naming		−0.03	0.09	0.13	.721
Response inhibition		0.18	0.10	3.13	.080
Cognitive flexibility		0.12	0.10	1.58	.213
Verbal working memory		0.24	0.08	8.41	.005

Note. N = 125. Sex was scored as male = 1 and female = 0. RAN was scored with higher values (i.e., more time) indicating lower performance.

Table 5
Summary of significant executive functioning predictors of mathematics and emergent literacy skills.

	Response inhibition	Cognitive flexibility	Verbal working memory
Numeracy skills			
Subitizing	*		
Set comparison			
Verbal counting sequence	**		
One-to-one correspondence	***		
Cardinality (how many)	**	***	
Cardinality (count a set)	*	*	
Numeral identification		+	
Set-to-numerals	**		
Number order	**	*	**
Number comparison			**
Story problems	**		*
Formal addition			+
Emergent literacy			
Definitional vocabulary			
Print knowledge	***	**	
Phonological awareness			*

+Significant until application of Benjamini–Hochberg correction.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Cognitive flexibility

In examining the relations between CF and the components of mathematics and literacy, we did not have any specific hypotheses due to a lack of empirical work in this area. However, based on theory, we thought it was likely that CF would be related to more complex and abstract math skills. We found that CF was related to a narrow range of mathematics skills—particularly those that required more conceptual or abstract knowledge. Specifically, it was significantly related to only 3 of the 12 measures of mathematics (both measures of cardinality and number order) and marginally significantly related to numeral identification. It was also significantly related to print knowledge but not to definitional vocabulary or phonological awareness.

Discussion

The results from this study generally support our hypotheses that the components of EF are distinctly related to components of early mathematics and literacy. These relations appear to follow a developmental framework where more cognitively complex aspects of EF are related to more complex or abstract aspects of mathematics and literacy. This research expanded on prior work that has taken componential views of both EF and academic skills (Espy et al., 2004; Lan et al., 2011; LeFevre et al., 2010; McClelland et al., 2014) in two ways. First, these relations were examined at a more nuanced level and, second, a more comprehensive approach was taken by including a broad spectrum of mathematics and literacy measures within one study. Critically, the distinct relations identified lay a foundation for better understanding the ways in which EF skills are related to specific academic skills.

Key findings

Response inhibition

In contrast to Lan and colleagues (2011), RI emerged as a broad predictor of early mathematics skills. The main exceptions to this finding were three of the tasks that involved print-related concepts (numeral identification, number comparison, and formal addition). The ability to inhibit natural responses while engaging in math plays a significant role in performance on a broad range of mathematics skills. Children must call on RI to succeed on math tasks, resisting the natural inclination to either abandon the task or use a previously learned rule that might no longer apply (Bull et al., 1999).

In terms of literacy, our results shed light on some of the inconsistencies found in previous work. Our findings reveal that RI is significantly related to print knowledge, but not to phonological awareness, which partially aligns with Allan and Lonigan (2011), who found that RI was related to each literacy domain measured. Our findings also indicate that RI is not related to definitional vocabulary, which is similar to the findings of McClelland and colleagues (2014). Inhibiting a prepotent response appears to have more utility for children as they are engaging in literacy tasks related to print that require more than just general cognitive ability.

Working memory

Similar to prior findings with preschool and early elementary school children (Lan et al., 2011; Purpura & Ganley, 2014; Simmons, Willis, & Adams, 2012), WM was related to complex mathematical skills, including order/magnitude of numerals and computation. Each of these tasks also requires children to complete multiple steps in order to answer correctly. For example, to complete the number comparison task, children needed to intake (visually or aurally) the four numerals, compare their magnitudes, and identify the largest.

Regarding literacy, as expected, a significant relation was found between WM and phonological awareness. This is likely because, for phonological awareness, children must hold multiple sounds or words in memory, combine or separate them, and then output a new word. However, despite previous evidence suggesting that WM may be related to vocabulary (McClelland et al., 2014), that relation was not found in the current study. The lack of a relation is likely because vocabulary and print knowledge do not require manipulation of information in memory; rather, they simply require output of known information. Overall, the findings support the predicted hypothesis that the more complex aspects of mathematics and literacy would be predicted by WM.

Cognitive flexibility

The limited prior evidence on the relation between CF and academic skills has been somewhat mixed (Blair & Razza, 2007; Bull et al., 1999; Espy et al., 2004; Lan et al., 2011); however, based on theoretical perspectives noted earlier (Best & Miller, 2010; Diamond et al., 2002), it was believed that CF would be primarily related to more abstract aspects of mathematics and literacy. CF appears to be narrowly related to a specific subset of skills that have often been identified as some of the most critical in the development of their respective domain. Most notably, CF is related to two abstract areas of academic skills: cardinal number knowledge and print-related skills (both numerals and letters). When children transition from applying the counting sequence to sets (one-to-one correspondence) to obtaining quantity, they move from thinking about counting as a procedure to thinking about it as a conceptual process. Essentially, they must change their thinking and flexibly move from the procedural task of counting to understanding counting as providing quantitative information. Similarly, print-related skills in both mathematics and literacy require children to flexibly move between different levels of representation. Dehaene (1992), in the triple-code model of numerical representation, indicates that when individuals view numerals, they internally represent them in an analogue manner—essentially switching between representations. Similarly, and consistent with previous literature (Bierman et al., 2008), in literacy-related print knowledge children must shift between using names and sounds (sometimes different sounds) as appropriate. Presumably, the ability to flexibly move between these representations and uses of print may require well-developed CF.

Implications

The differential associations between components of EF and academic skills may explain why longitudinal studies measuring purportedly the same aspects of EF and academic components have obtained differential findings. One of the typical measures used to assess mathematical abilities is the Woodcock-Johnson III Applied Problems subtest. As this task progresses, the nature of the skills assessed changes; thus, it is also reasonable to expect that the relation of components of EF to this task would also change dependent on the level at which the students are typically performing. Similarly, the Woodcock-Johnson III Letter-Word Identification subtest initially measures print knowledge but progresses toward measuring phonological awareness or word knowledge. Dependent on the overall ability level of the children in a targeted sample, the relation between broad measures of academic achievement may vary as a function of the types of items at that ability level. Importantly, the ability level (and test items administered) may change both within and across ages, based on sample population characteristics such as socioeconomic status, classroom quality, and disability status. Thus, the relations of EF to academic outcomes may be affected not only by the specific measures used but also by sample characteristics (McClelland & Cameron, 2012; Wanless et al., 2011). Careful consideration regarding the selection of tasks based on research questions and target populations should be considered for both longitudinal and intervention studies as well as potentially using assessments of specific components of academic domains rather than using broad assessments.

These differential component relations may also be important to consider in designing and evaluating the effectiveness of mathematics and literacy interventions because both domains are taught at component levels (e.g., curricula include specific instructional activities for each aspect of mathematics and literacy such as counting and phonological awareness). Understanding how particular components of EF are related to aspects of mathematics and literacy may enable intervention developers to better account for EF in the construction of their activities. Appropriate scaffolding of instructional activities that accounts for the cognitive demands of each academic component may be a potential avenue for enhancing intervention effectiveness. For example, instruction on more complex mathematics skills or phonological awareness may need to take into account WM demands, whereas instruction on print concepts in both mathematics and literacy may need to take into account CF requirements. Additional work should be conducted to determine whether this would be a beneficial mechanism for integrating instruction across domains.

Limitations and future directions

The findings from this study provide a more nuanced examination of the relations between EF and academic skills than has previously been investigated. However, there are several key limitations that must be noted. First, data from this study were collected concurrently and, thus, cannot be used to make causal inferences or conclusions about the relations between growth in EF and growth of mathematics and literacy skills. It is possible that the results of this study are due to age-related changes in the sample; as children age, and as different EF skills develop (e.g., CF begins development later than RI), the EF skills may simply develop in parallel with specific mathematics and literacy skills. Notably, it may be that the measurement of EF and academic skills, as well as the relation between domains, changes with age. For example, some research has found that EF skills at the earliest ages are unidimensional (Hughes et al., 2010; Wiebe et al., 2008) and then begin to separate at around 5 years of age (Lerner & Lonigan, 2014). This may indicate that the nature of what is being measured by the EF constructs changes over these early ages and, thus, their relation to mathematics and literacy may change. However, in the current study, partial correlations between the EF components were generally small and sometimes nonsignificant, especially when age was taken into account, indicating that they do seem to be measuring discrete constructs. Future longitudinal research that includes a sample with a more narrow age range and broader range of EF measures is needed to evaluate this issue.

Second, despite the depth of covariates used in the study and the logical and distinct pattern of findings identified, it is possible that the results of the study are due to the issue of *task impurity* (Huizinga et al., 2006; Miyake et al., 2000) given that we used only one measure of each EF construct. To address the issue of task impurity, scholars have suggested using multiple measures of each EF component (Miyake et al., 2000). It is important to note, however, that EF assessments suitable for preschool children might not be as susceptible to task impurity because the majority are relatively simple and, in contrast to more complex adult tasks, might not require significant levels of unmeasured cognitive processes (Best, Miller, & Jones, 2009). Furthermore, it is also possible that by using only one measure of each component of EF, the relations between EF tasks and academic skills may be a result of measurement methods; specific aspects of a task administration rather than the construct itself may be the reason for the targeted relations. Given the large numbers of mathematics, literacy, and EF tasks administered in this study, a balance between depth of measurement across constructs was needed—particularly given the age of the sample population. In the current study, time constraints on the overall testing battery limited us from assessing children more in depth on all domains. Importantly, the findings from this study set a foundation for future more targeted work that uses a greater depth of EF tasks across each construct and a more select set of mathematics or literacy assessments to better address the issues of task impurity and measurement concerns.

Third, the sample was relatively homogeneous and had higher levels of parental education than the general population. Thus, findings might not be generalizable to more heterogeneous populations and specifically to children from families with lower educational attainment. Additional research with more diverse samples is needed.

Fourth, the internal consistencies of two dependent variables (subitizing and formal addition) were relatively low, which may have limited the variance accounted for by the independent variables; however, the findings for those measures align with theory and previous research.

Conclusion

The current study provides evidence that the components of executive functioning are distinctly related to individual components of early mathematics and literacy. This study extends the literature by including all three EF components in analyses as well as several distinct components of early mathematics and literacy. This enables us to limit potential confounds such as proxy relations. Our findings suggest that response inhibition is broadly related to aspects of mathematics and emergent literacy, working memory predicts the complex aspects of mathematics and literacy, and cognitive flexibility is most associated with the more conceptual or abstract components of mathematics and literacy. These findings highlight the importance of investigating individual components of EF and early academic skills and have broader implications for measurement of these domains.

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