

KINDERGARTEN FINE MOTOR SKILLS AND EXECUTIVE FUNCTION: TWO
NON-ACADEMIC PREDICTORS OF ACADEMIC ACHIEVEMENT

by

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ABSTRACT

KINDERGARTEN FINE MOTOR SKILLS AND EXECUTIVE FUNCTION: TWO NON-ACADEMIC PREDICTORS OF ACADEMIC ACHIEVEMENT

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Recent research has found that children's fine motor skills and executive function prior to elementary school are associated with later academic achievement. The current study explored this association further by examining these two constructs in relation to children's growth in math and reading achievement through 8th grade using the Early Childhood Longitudinal Study-Kindergarten cohort, a large-scale, longitudinal dataset. Fine motor skills were measured in the Fall of kindergarten using seven items from the Early Screening Inventory – Revised (ESI-R; Meisels, Marsden, Wiske, & Henderson, 1997). Executive function was measured using the Approaches to Learning and Self Control subscales of the Social Rating Scale (SRS; Meisels & Atkins-Burnett, 1999), a teacher report completed in the Fall of kindergarten. Fine motor skills and executive function were used to predict growth in math and reading achievement using achievement scores collected at six time points from kindergarten through the end of middle school.

These achievement scores were used to create two growth models in a structural equation modeling (SEM) framework using AMOS software (Arbuckle, 2003) – one for math and one for reading. Fine motor skills and executive function were entered into the SEM as predictors of growth in achievement. In order to understand potential moderating effects of executive function, multigroup analysis was also used to determine if the associations between these non-academic skills and children’s achievement trajectories differed depending on kindergarten executive function skills. Findings indicated that both fine motor skills and executive function measured at kindergarten entry predicted growth in math and reading achievement through middle school after controlling for gender, socioeconomic status, and early math and reading skills. These associations were positive, such that starting kindergarten with better fine motor skills or executive function ratings was related to steeper rates of growth in both math and reading. Additionally, there were significant differences in achievement growth based on the high and low executive function groups. Children who started kindergarten with high executive function skills grew academically at a greater rate than those who started with low executive function skills. Previous studies linking fine motor skills and executive function to achievement have not explored the association between these two skills and growth in achievement. Rather, research has primarily focused on single time points of achievement in elementary school. Therefore, the present study provides new information about these associations further into children’s academic careers, as well as examining links with growth in achievement over time. Possible implications for educational

practices are discussed, including the potential need for more explicit instruction in these areas in early childhood.

KINERGARTEN FINE MOTOR SKILLS AND EXECUTIVE FUNCTION: TWO NON-ACADEMIC PREDICTORS OF ACADEMIC ACHIEVEMENT

In recent years, there has been increased interest in promoting academic achievement in early childhood and during the transition to elementary school (Snow, 2006). While factors such as gender, socioeconomic status, and the early math and reading abilities that children have when they begin school remain clearly and strongly linked to achievement (Blair, 2002; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Rimm-Kaufman & Pianta, 2000), two additional early indicators of achievement have also been identified. Fine motor skills and executive function prior to first grade have both been linked to children's academic achievement. Although these two skills are not taught directly in the classroom, they appear to be associated with children's achievement both concurrently and longitudinally (Carlson, Rowe, & Curby, in press; Duncan et al., 2007; Grissmer et al., 2010; Murrah, 2010; Son & Meisels, 2006).

Previous longitudinal research into these associations has focused on performance through elementary school (i.e., Grissmer et al., 2010; Murrah, 2012; Son & Meisels, 2006). In order to gain a better understanding of how these skills, measured in kindergarten, are associated with children's achievement throughout elementary and middle school, the current study examined the associations between fine motor skills and executive function and children's growth in math and reading achievement over eight years – from kindergarten to 8th grade. By including 8th grade achievement scores, this

study provides information about the long-term influence of fine motor skills and executive function through middle school – a time when the learning environment and children’s cognitive skills are changing (Midgley, Anderman, & Hicks, 1995; Wigfield, Lutz, & Wagner, 2005).

Additionally, considerations of the potential interactions between fine motor skills and executive function in predicting academic growth have only recently been explored. The one available study found a compensatory effect for executive function such that children with poor fine motor skills showed improved academic achievement when they had good executive function (Cameron et al., 2013). However, this study looked at single time point outcomes within early childhood, whereas the current study explores interactions with growth in achievement through middle school. Because of this methodological difference, the effects of such an interaction may be different than those was found by Cameron and colleagues (2013). For instance, it may be that children who are strong in both fine motor skills and executive function make the greatest gains in math and reading achievement; or it may be that being strong in one of these area acts as a protective factor for children who are low in the other area. Additionally, there may not be an interaction, indicating that each ability is uniquely associated with achievement. In order to better understand such possible interactions, the present study examines early executive function skills as a possible moderator of the association between early fine motor skills and achievement (math and reading) growth through 8th grade.

The current study uses data from the Early Childhood Longitudinal Study – Kindergarten cohort (ECLS-K) to examine these associations. The ECLS-K is a large-

scale longitudinal study originally designed to assess children's learning-related experiences starting in kindergarten (Tourangeau, Nord, Le, Sorongon, & Najarian, 2009). In order to examine associations, measures of fine motor skills and executive function completed in the Fall of kindergarten were used as predictors of growth in achievement based on six measures of math and reading achievement administered through 8th grade. Understanding how these constructs contribute to academic achievement provides important information that has the potential to positively influence children's achievement trajectories. For instance, if these constructs are associated with growth in achievement over time, this would suggest that children's academic performance may benefit from more explicit instruction in fine motor skills and executive function.

Fine Motor Skills

Fine motor skills are broadly defined as the manual dexterity involved in coordinating muscle movements in the fingers (Essa, Young, & Lehne, 1998), and primarily rely on the prefrontal cortex (PFC) and cerebellum (Diamond, 2000). This includes the basic control of small muscle movements, which govern such abilities as finger dexterity, motor sequencing, and fine motor speed and accuracy (Davis & Matthews, 2010). Fine motor skills often also involve the incorporation of visual stimuli from the environment (Korkman, Kirk, & Kemp, 2007). Whenever children grip a pencil, tie their shoes, or write their names, they are relying on their fine motor skills.

In a school setting, fine motor skills can become quite complex when children must perform tasks such as copying images, letters, or numbers in pencil-and-paper tasks,

as this requires them to use visual information from the environment in combination with small muscle control to reproduce an image or figure (Carlson et al., in press; Sorter & Kulp, 2003). Such tasks involve processing visual input, creating a mental representation of that information, and then accurately reproducing that image (Sorter & Kulp, 2003). Carrying out fine motor tasks in the classroom is likely to place heavy cognitive demands on young children, as many of the processes described above are complex and often not practiced or automated for kindergarteners. Fine motor skills in general are often measured using drawing, copying, and block-building tasks, which capture the various ways that fine motor skills may come into play in a classroom setting.

Executive Function

Definitions of executive function (EF) are varied, but the general consensus is that this construct is made up of a number of cognitive processes that are essential for planning and problem-solving, and rely on PFC areas of the brain (Best & Miller, 2010; Graziano, Reavis, Keane, & Calkins, 2007; Zelazo, Carter, Reznick, & Frye, 1997). In adults, these skills are often considered to be three distinct abilities: inhibitory control, working memory, and shifting/updating (Miyake et al., 2000; St. Clair-Thompson & Gathercole, 2006). However, in early childhood, aspects of EF are more fluid and difficult to distinguish (Best & Miller, 2010; Blair & Razza, 2007; St. Clair-Thompson & Gathercole, 2006) and research suggests that EF may be best represented by two abilities: attention and self-control (Blair & Razza, 2007; Shonkoff & Phillips, 2000). Attentional and self-control skills lay the foundation for later EF development (Garon, Bryson, & Smith, 2008; McClelland et al., 2007), and are reliable predictors of school performance

and academic achievement (Blair & Diamond, 2008). EF is also at play in the classroom when children have the attentional and self-control skills necessary to stay on task and work independently (Best & Miller, 2010; Hughes, 1998).

In early childhood the development of EF varies based on the underlying component being considered. For instance, many self-control and attentional processes show rapid improvement from ages 3 to 5, although improvement can continue well into adolescence (Best & Miller, 2010; Carlson, 2005). However, it is difficult to determine a specific developmental sequence, as abilities may vary drastically based on the type and difficulty of the task (Best & Miller, 2010). Overall, studies suggest that broad attentional skills may level off in their development before self-control skills do (Anderson, 2002; Romine & Reynolds, 2005). Importantly, regardless of developmental sequence, such early EF skills are highly associated with later EF skills (Eigsti et al., 2006; Hughes & Ensor, 2007). Therefore, the skills measured in the current study, which tap into key components of early EF, are representative of EF skills throughout all of childhood and into adulthood.

Children's ability to pay attention and complete tasks in a learning environment contributes to their academic success. This includes paying attention to a teacher's lessons and completing classroom activities. Similarly, self-control that leads to academic success focuses more specifically controlling one's emotions and behaviors in order to interact appropriately with teachers and other students. Children who are in better control of their behavior and emotions are likely to have more control over the focus of their attention as well. Self-control also enables children to have more harmonious

relationships with others, which is known to facilitate more successful learning and academic performance (Denham et al., 2011; Ladd, 1990).

Attention can be understood as a child's ability to focus appropriately and stay on task, often over an extended period of time and in the presence of distractions (Ruff & Lawson, 1990; Ruff & Rothbart, 2001). In the kindergarten classroom such attentional skills are necessary to listen to the teacher, follow simple and multi-step directions, and persist in various goal-directed behaviors (Garon et al., 2008; Saez, Folsom, Otaiba, & Schatschneider, 2012). Attention is also important for retaining information, as children must attend to a lesson or activity for long enough that the information can be processed and stored in long-term memory (Saez et al., 2012). Behaviorally, attention can be seen in action when children listen and remain engaged during morning meeting or stay focused on a drawing until it is complete. Although many kindergarteners can complete such tasks, attentional skills are extremely variable between children at this age (Janvier & Testu, 2007).

Children with better attentional skills are generally able to focus on a classroom lesson longer than children with poorer attentional skills (McClelland, Morrison, & Holmes, 2000), thus enabling them to engage with the information that is being taught to them. Additionally, many early childhood learning opportunities are centered around classroom activities, so young children who are able to stay on task are more likely to participate in and complete such activities. Attention and other EF skills in kindergarten have been consistently shown to predict long-term achievement (Duncan et al., 2007; McClelland et al., 2000). In a large-scale empirical study Duncan and colleagues (2007)

determined that after early math and reading abilities, ratings of attention, learning independence and flexibility in early childhood were the next best predictor of later academic achievement. More specifically, McClelland and colleagues (2000) determined that EF skills, such as staying on task and completing classroom work in kindergarten were related to math and reading performance in second grade. Overall, children who attend to classroom lessons and complete classroom tasks tend to perform better academically than those who struggle in these areas.

Self-control is another important component of early EF, and can be conceptualized as the intentional cognitive and behavioral processes that are used to control emotions and behavior so that the individual can function in such a way that is appropriate, adaptive, and beneficial in a given setting (Blair, 2000; Blair & Diamond, 2008). Teachers often report that self-control skills are the most important component of school readiness (Blair & Diamond, 2008; Rimm-Kaufman, Pianta, & Cox, 2000), and self-control has been linked to school success (Graziano et al., 2007; McClelland, Acock, & Morrison, 2006; Rimm-Kaufman et al., 2009). For example, Graziano and colleagues (2007) found that when learning new information in school, children who had difficulty controlling their emotions often became frustrated and anxious, and their lack of control over their feelings made it hard for them to learn that new information. Importantly, the association between poor self-control and poor academic performance was present before children started elementary school. Similarly, McClelland and colleagues (2006) found that children with poor self-control in kindergarten not only had low kindergarten math

and reading scores, but they continued to fall farther behind their peers throughout elementary school.

Self-control is also an important contributor to social relationships with teachers and peers in the classroom (Eisenberg, Valiente, & Eggum, 2010), which influence children's school performance (Eisenberg et al., 2010; Ladd, 1990; Valiente, Lemery-Chalfant, Swanson, & Reiser, 2008). Valiente and colleagues (2008) found that children who had difficulty controlling their behaviors in the classrooms had poor relationships with their teachers, and these negative relationships were associated with declining grades and increasing absences over the course of the school year. Eisenberg and colleagues (2010) reached similar conclusions about the importance of self-control in an early childhood setting in an extensive review of articles examining the association between this construct and academic achievement. Overall, the authors concluded that children who were better able to control their behaviors and emotions were more engaged in the learning process and had higher levels of academic achievement compared to children who had less self-control. Children who do not control their behavioral and emotional responses in the classroom well are less likely to stay engaged in academic lessons, as well as less likely to maintain positive relationships with peers and teachers – both being linked to poorer long-term academic achievement.

Relations Between Fine Motor Skills and Executive Function

Fine motor skills and EF are interrelated in their development (Diamond, 2000), and the one available study suggests that they may be uniquely associated with achievement (Cameron et al., 2012). Fine motor skills and EF both develop in the

prefrontal cortex (PFC), indicating an early relation between these two skill sets (Best & Miller, 2010; Diamond, 2000). In regards to associations in an academic setting, sensory and motor networks in the brain must coordinate motor activity with attentional and regulatory processes in order to complete most academic tasks (Blair, 2002; Murrah, 2010). For instance, for a child to practice writing the alphabet by copying the letters written on a worksheet, he has to visually process the letter he wants to write, position his fingers correctly on the pencil, move the pencil so that it correctly forms the letter, keep his attention on the task, and remember the goal of the task, all while ignoring distracting stimuli. This is particularly daunting in kindergarten, when many of these processes have not yet been automated.

Although EF and fine motor skills are interrelated in some ways, including at the neurological level (Best & Miller, 2010; Blair, 2000; Diamond, 2000), they are also unique. Attention and self-control are necessary for many classroom-based activities that do not involve fine motor skills, such as listening to a story or watching a demonstration. Many fine motor skills become automated in early childhood, so they can be completed with little to no allocation of EF resources (Diamond, 2000). In other words, once you are able to easily hold a pencil and write your name, you no longer have to allocate attentional resources in order to correctly place your fingers on the pencil or move that pencil to form individual letters – EF is primarily needed to complete non-automated tasks. As stated above, both fine motor skills and executive function are needed for most academic tasks (Blair, 2002), but research has found that each construct contributes uniquely to achievement (Cameron et al., 2012).

Mechanisms of Influence on Academic Achievement

Two broad approaches can be used to explain the mechanisms by which fine motor skills and EF influence children's achievement: brain structure and development, and cognitive load.

Brain Structure and Development.

Fine motor skills. It has been proposed that the first way children learn is by gaining intentional control of their early muscle movements (Adolph 2005; Campos et al., 2000; Piaget, 1953). As children learn new motor skills they must unify the sequences required for each action into an organized mental framework, and this need for organization places increasingly complex demands on the developing brain (Campos et al., 2000). It is through this process that cognition develops in response to the demands of early motor learning (Adolph, 2005). In addition to driving cognitive development forward, early motor development can also be seen as the key event that is needed for many other areas of development to take place. Bushnell and Boudreau (1993) point to early motor development as the starting point for cognitive development, because without movement it would be difficult for children to have the types of interactions with the world that lead to advanced cognition.

Neuroimaging has also provided strong evidence of a relation between fine motor and cognitive skills. The PFC, cerebellum, and basal ganglia are activated for both motor and cognitive tasks (Diamond, 2000; Willingham, 1999). Studies of typically-functioning populations have indicated overlaps between PFC and cerebellum activation for both fine motor and cognitive tasks and studies of patients with brain damage indicate that damage to either structure often results in impaired functioning for both types of skills (Diamond,

2000). The overlapping activation patterns seen for both cognitive and motor tasks suggest a process of development in which better fine motor development may lead to better cognitive development (Adolph, 2005; Campos et al., 2000), which in turn leads to stronger academic achievement (Carlson et al., in press).

These associations may also be due to the underlying neural network that serves both perceptual motor and cognitive processing, which links both areas consistently across childhood (Davis, Pitchford, & Limback, 2011; Diamond, 2000). There is evidence that motor activity can improve brain functioning, especially in the PCF, as well as improving cognitive and language skills in general (Leiner, Leiner, & Dow, 1991). The link between fine motor development and achievement is especially strong when relating fine motor skills to math achievement (Carlson et al., in press; Son & Meisels, 2006). This may be, in part, because numerical understanding and visual-spatial processing have both been linked to the parietal cortex (Bueti & Walsh, 2009; Dehaene, Molko, Cohen, & Wilson, 2004). Children learn about scale, dimension, and size by interacting with their environments and such interactions are, by necessity, fine motor related. Therefore, mathematical number knowledge and fine motor tasks involving the integration of visual input with fine motor output in the parietal cortex. An understanding of numbers builds off of an understanding of general magnitude, which is linked to motor development in the brain (Bueti & Walsh, 2009). Such numerical skills lay the foundation for math skills and development, which may explain the stronger associations between fine motor skills and math performance.

Overall, children who have better fine motor skills prior to first grade are more likely to have resulting greater cognitive capacities, thus making them better prepared for an academic learning environment (Cameron et al., 2012; Carlson et al., in press; Grissmer et al., 2010). It may also be that the skills necessary for school-based learning are strongly rooted in fine motor actions like writing and drawing (Carlson et al., in press). Therefore, children who do not struggle with such tasks may be better prepared for school success than those who do.

Executive Function. Neuroimaging has also indicated links between EF and achievement. The anterior cingulate cortex (ACC) has been linked to self-control behaviors (Bechara, Damasio, Damsio, & Anderson, 1994) and to cognitive tasks that require children to detect and correct errors (Bush et al., 2000). ACC volume has also been found to be positively associated with performance on both cognitive and self-control tasks in fMRI studies of children (Bush et al., 2000), indicating a potential benefit for cognitive performance based on enhanced self-control in early childhood. The dorsolateral prefrontal cortex (DPFC) has been linked to attentional behaviors (Bush et al., 2000) and to difficult cognitive tasks that have not yet been automated (Diamond, 2000). This indicates an overlap in functionality for EF and cognitive (academic) ability.

Children's self-control and attentional abilities are also at play within the behavioral activation and inhibition systems in the PFC, nucleus accumbens, and amygdala (Blair & Diamond, 2008). These systems help children control their emotions and behaviors and pay attention to material in the classroom. However, these systems are often not well-developed in young children (Blair & Razza, 2007). When children

struggle to pay attention and control their behaviors and emotions in kindergarten they are likely to fall behind their peers cognitively and academically, putting them at a disadvantage before they even start elementary school.

As with fine motor skills, research suggests that links between EF and achievement are stronger for math achievement (Murrah, 2012). The development of EF skills and complex conceptual math understanding share similar areas in the PFC (Blair et al., 2007), and neuroimaging studies have shown that there is greater overlap in brain activation for EF and math tasks, as compared to reading tasks (Blair & Razza, 2007; Houde, Rossi, Lubin, & Joliot, 2010). Having strong EF skills in early childhood is also beneficial for children's long-term reading achievement, just not to the same degree as they are for long-term math achievement – an association that has been found when examining reading achievement outcomes through 5th grade (Murrah, 2010).

Cognitive Load

The second possible mechanism linking fine motor skills and EF to academic achievement is cognitive load, or cognitive resource depletion. Cognitive load theory states that people have the capacity to process a finite amount of information at any given time, and the difficulty of the information being processed influences how efficient or accurate we are in whatever task is being completed or skill is being learned (Paas, Renkel, & Sweller, 2004; Sweller, 1988). For example, solving a simple addition question requires fewer cognitive resources than solving a more complex algebra problem. Additionally, if you are trying to solve that algebra problem while the TV is on and your friend is talking, it becomes even more difficult. This is because you have to use

more cognitive resources to block out the distracting stimuli and focus on solving the equation (Paas et al., 2004).

This mechanism is related to the brain-based explanations for links between fine motor skills, EF, and academic achievement. As established above, processes in the brain are interrelated, and when one process is automated, activation in related brain regions decreases, meaning that more cognitive resources are available to be deployed to another operation (Diamond, 2000; Paas et al., 2004). For example, children who have good fine motor skills do not have to focus on how to hold their pencil while copying notes from the board, so it is easier for them to absorb the information from the lesson. This same rationale can be used to explain the link from EF to achievement. Children with strong EF skills who are engaged in the learning process do not have to struggle to pay attention to their teacher during a lesson, or ignore distracting stimuli that could take focus away from the teacher, thus making it easier for them to take in the information from the lesson. These EF and fine motor skills are not taught directly in school, but children who are stronger in these two domains will have more resources free to devote to the lessons they are being directly taught. Both mechanisms by which fine motor skills and EF influence children's learning and subsequent academic achievement over time illustrate the importance of these two skills prior to the beginning of elementary school.

Other Factors Related to Achievement

Numerous child-level factors are associated with children's academic performance, including gender, socioeconomic status, and children's early math and reading abilities. For instance, children from higher-SES backgrounds are more likely to

be equipped with the skills necessary for school success before they begin kindergarten than children from lower-SES backgrounds (Magnuson & Shager, 2010). This early disparity leads to noticeable performance differences when children first start school, but it also continues to have a problematic effect in later years. Beginning school at a deficit can negatively impact performance in later grades and result in an ongoing and widening achievement gap between those of higher- and lower-SES status (Reynolds & Temple, 2006).

As with differences in achievement based on socioeconomic status, gender differences in achievement can be seen as early as preschool (Chen, 2010). Although boys and girls show similar performance on standardized achievement tests, girls often show better academic performance in a school setting (Duckworth & Seligman, 2006). This can be partially attributed to behavioral differences, as boys tend to display higher rates of behavior problems compared to girls (Chen, 2010; Winsler et al., 2008), which negatively impacts classroom-based evaluations such as grades.

In addition to the two previously mentioned child-level factors, the academic skills that children have when they begin formal schooling are likely to be a key factor in later achievement as well. Learning is a structured process and it builds upon itself so that knowledge in specific areas contributes to the ease with which new information and skills can be integrated (Pungello, Kupersmidt, Burchinal, & Patterson, 1996). Overall, children with stronger early math and reading abilities at school entry are better prepared to learn new information in the future (Duncan et al., 2007; La Paro & Pianta, 2000; Stevenson & Newman, 1986). For these reasons, the present study included

socioeconomic status, gender, and children's math and reading scores in the Fall of kindergarten as control variables, thus determining whether or not fine motor skills and EF are associated with math and reading achievement after controlling for other factors that have been previously linked to achievement.

THE CURRENT STUDY

Children's kindergarten fine motor skills and executive function are important contributors to long-term academic achievement. EF is needed for processing complex cognitive information and staying on task in a learning environment. Fine motor skills are needed to complete and eventually automate many academic tasks. These skills have generally all stabilized by the time children enter kindergarten (Best & Miller, 2010; Son & Meisels, 2006), and can therefore be successfully measured and followed longitudinally to determine their relations with math and reading achievement throughout elementary and middle school.

The current study explores growth in achievement over time from kindergarten to 8th grade, while previous research in this area has primarily focused on performance through 5th grade. From 5th to 8th grade there are marked changes in the learning environment and in children's cognitive abilities. Generally speaking, children's classroom grades begin to decline after elementary school (Barber & Olsen, 2004). This is often a result of declines in motivation, changing relationships with others, and differences in the structure of school itself. Such changes can also be attributed to the increasing demands of the middle school environment (Barber & Olsen, 2004; Burchinal, Roberts, Zeisel, & Rowley, 2008; Midgley et al., 1995). Cognitive abilities also change drastically from 5th to 8th grade, as children's reasoning, abstract thinking, and problem-

solving abilities become more advanced (Bullock & Ziegler, 1999; Kuhn, Black, Keselman, & Kaplan, 2000; Wigfield et al., 2005; Zimmerman, 2007). These changes contribute to the differences in achievement that may be seen between 5th and 8th grade. Within the context of the present study, these differences highlight the need for assessing associations between fine motor skills and EF and growth in achievement beyond 5th grade. Information about the effects of early non-academic skills on long-term growth in achievement is more complete with the inclusion of 8th grade performance.

The current study answers the following research questions:

1. Do fine motor skills measured in kindergarten predict growth in children's math and reading achievement from kindergarten to 8th grade after controlling for socio-economic status, gender, executive function, and math and reading skills measured in the Fall of kindergarten?
 - a. I hypothesize that fine motor skills will be associated with growth in math and reading from kindergarten through 8th grade such that children with better fine motor skills will also greater growth in math and reading performance through middle school. Early fine motor development has been tied to cognitive development (Diamond, 2000), so children with strong fine motor skills in kindergarten are likely to show associated gains in math and reading performance. Additionally, fine motor tasks that have not been automated will tax children's cognitive resources, reducing the resources that children have available for attending to classroom lessons and tasks. Once such tasks are automated, activation in the PFC decreases

(Willingham, 1999), freeing up resources for other learning-related activities.

2. Do executive function skills measured in kindergarten predict growth in children's math and reading achievement from kindergarten to 8th grade after controlling for socio-economic status, gender, fine motor skills, and math and reading skills measured in the Fall of kindergarten?
 - a. I hypothesize that executive function will be associated with greater growth in math and reading achievement from kindergarten through 8th grade. Early EF skills are necessary to function in the classroom, where children must attend to lessons and rules, and control their emotions and behaviors in the face of distracting and provocative situations (Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009). Poor self-control has been shown to hinder many cognitive processes (Blair, 2002; Graziano et al., 2007), as children who cannot inhibit inappropriate behavioral and emotional responses cannot focus on the lesson at hand. This may also contribute to impaired attention in the classroom (Blair, 2002), disrupting children's ability to focus and learn. Therefore, children with better executive function skills in the Fall of kindergarten will have steeper growth in math and reading achievement through 8th grade.
3. Are the associations between fine motor skills and executive function stronger for math than for reading?

- a. I hypothesize that fine motor skills and EF will both be more strongly associated with math than with reading. Previous research evaluating associations between fine motor skills and achievement has found stronger relations with math than reading (Carlson et al., in press; Son & Meisels, 2006). Similarly, good early EF skills have been found to be most beneficial for children's math achievement (Murrell, 2010). Additionally, evidence from neuroimaging research suggests strong relations between fine motor and EF skills and children's performance on math tasks (Blair et al., 2007; Bueti & Walsh, 2009), suggesting that this link is present early on at the neurological level. Therefore, I expect to find stronger associations with growth in math achievement than growth in reading achievement.
4. Is the association between kindergarten fine motor skills and growth in math and reading achievement moderated by kindergarten executive function skills?
 - a. I hypothesize that there will be an interaction between EF and fine motor skills, such that EF skills will provide a compensatory effect for poor fine motor skills in kindergarten. In other words, children with poor fine motor skills in kindergarten will always show less growth in achievement than those with average or strong fine motor skills, but if they have good kindergarten EF skills the difference in growth will not be as large. Their achievement slopes will be steeper than they would have been without the aid of good EF skills. Such a compensatory effect should exist because EF

and fine motor skills have been found to have unique associations with achievement (Cameron et al., 2012). Children with poor fine motor skills will likely benefit more from good EF skills than children with good fine motor skills who are already demonstrating associated gains in achievement.

METHOD

Participants

The ECLS-K dataset contains information about children's school experiences from kindergarten through 8th grade. Data collection began during the Fall of the 1998-1999 school year and initially included 21,260 kindergarteners throughout the United States. The ECLS-K selected children for participation using a multistage probability sample design. This involved starting with 1,335 counties across the country, then selecting 1,280 public or private kindergarten programs from within those counties, then selecting 24 children from each public program and 12 from each private program (Tourangeau et al., 2009).

Data collected included information from parents, teachers, and principals, student records, and numerous direct child assessments. Data were collected for all children in the Fall and Spring of kindergarten, and the Spring of 1st, 3rd, 5th, and 8th grades (Tourangeau et al., 2009). The ECLS-K includes assessments of children's fine motor skills and executive function measured in the Fall of kindergarten. This information can be used to assess the relation between these skills and children's later elementary and middle school achievement. The ECLS-K did not carry out direct assessments on children who had to be assessed using Braille or sign language, or whose Individualized Education Plan or Individualized Family Service Plan prohibited assessment. Therefore, these groups are excluded from the current study.

Additionally, children who had a language minority status, as determined by school records or teacher report, received an oral language proficiency assessment during the Fall and Spring of kindergarten and first grade. These students were included in the ECLS-K study, but the results of their proficiency test determined whether or not they would take the math and reading assessments, as well as in what language the assessments would be delivered (Rock & Pollack, 2002). Children who did not receive a proficient score on the language assessment in kindergarten or first grade were not administered the reading assessment. The math assessment was administered in Spanish for these students when appropriate. By third grade, students who were identified as language minorities in kindergarten were all able to complete the achievement assessments, so these students' data are included in the current study (Pollack et al., 2005a). Children were excluded from the current study if they had not completed at least three of the six math and three of the six reading assessments ($n = 9,641$). Although these criteria for exclusion are somewhat arbitrary, the decision was based on the fact that three or more time points are needed to appropriately model growth.

Attrition over the course of the study resulted in an 8th grade sample containing 12,129 children. Compared to the original kindergarten sample, the 8th grade cohort had a slightly higher percentage of White and Hispanic students, and a slightly lower percentage of Black and Pacific Islander students (Tourangeau et al., 2009). Compared to the kindergarten sample, the children remaining in the 8th grade cohort had a slightly higher percentage of parents who had some college, an undergraduate degree, or a Master's degree. Relatedly, the percentage of children with parents who had a high

school degree only was greater for children in the kindergarten sample (Tourangeau et al., 2009). The representation of public, religious, and private schools was similar in kindergarten and 8th grade (Tourangeau et al., 2009). This pattern of attrition should be considered when interpreting generalizability of the current results. This consideration is discussed in greater detail in the limitations section.

Measures

Fine motor skills. Fine motor skills were assessed in the Fall of kindergarten. The ECLS-K created a fine motor measure using seven items from the Early Screening Inventory-Revised (ESI-R; Meisels et al., 1997): replicating figures using ten wooden blocks, copying five figures, and drawing a person. Children could receive a score of 0-2 for the block building and draw-a-person tasks, and a score of 0 or 1 for each of the five figure-copying tasks. These items were summed, yielding a final composite score with a range of 0-9, with lower scores indicating worse fine motor skills (NCES, 2001).

Trained assessors administered the fine motor assessment in a one-on-one setting, often in children's schools or homes. Because fine motor skills are complex, and many of the neuromuscular processes that contribute to them are internal and unobservable (Barnett & Peters, 2004), direct assessment is the preferred method of measurement.

Content validity for the composite measure was assessed within the ECLS-K dataset using confirmatory factor analysis, which indicated that the seven fine motor items were representative of the same latent fine motor construct (NCES, 2001). Within the full ECLS-K dataset, Cronbach's alpha indicated an internal consistency of .57 for the full fine motor skills composite variable (NCES, 2001). Although this is not within the

desirable range for reliability, it is not unexpected given the dichotomous and trichotomous nature of the fine motor item (NCES, 2001; Son & Meisels, 2006).

This same fine motor composite has been previously used to predict children's achievement (Grissmer et al., 2010; Murrah, 2012; Son & Meisels, 2006), an association that has been established in previous literature using different samples (Cameron et al., 2012; Sorter & Kulp, 2003), indicating predictive validity for this measure. Additionally, assessments that use nearly identical tasks have been found to work well for children with diverse educational, cultural, and linguistic backgrounds (Beery & Beery, 2004; Korkman et al., 2007), suggesting that these tasks are likely to have good external validity.

Executive function. There are currently no large-scale datasets that contain direct assessments of executive function (Murrah, 2010), but the ECLS-K includes two subscales of the Social Rating Scale (SRS; Meisels & Atkins-Burnett, 1999) that are representative of early EF skills. The SRS is a teacher questionnaire that was adapted from the Social Skills Rating System (Gresham & Elliott, 1990) for use in the ECLS-K. The SRS asks teachers to rate how often children show certain behaviors on a 1-4, likert-type scale (*1 = Never, 4 = Very Often*). Teachers filled out the SRS for children in the Fall of Kindergarten.

Attention, learning independence, and organization are captured using the 6-item Approaches to Learning subscale of the SRS, which asks teachers to rate the frequency with which a child shows attentiveness, task persistence, eagerness to learn, learning independence, flexibility, and organization –behaviors that are primarily driven by

children's attentional skills. This subscale is meant to capture the behaviors that aid children in learning within a typical classroom environment (NCES, 2001). Self-control is captured using the 4-item Self-Control subscale of the SRS, which asks teachers to rate the frequency with which a child shows respect toward other children's property, controls his or her temper, accepts the ideas of his or her peers, and responds appropriately to peer pressure. This subscale is meant to capture behaviors that contribute to self-control in the classroom (NCES, 2001). Both subscales use averages to create their final aggregate scores, so possible scores for attention and self-control ratings range from 1-4 (NCES, 2001). These two subscales were averaged for the current study to create an aggregate EF variable. Previous work using the ECLS-K has only used the Approaches to Learning subscale as a proxy for EF (Grissmer et al., 2010; Murrah, 2012). The two subscales were combined in the current study because EF literature suggests that self-control skills are also an important component of EF in early childhood (Garon et al., 2008; Graziano et al., 2007; McClelland et al., 2006).

Content validity was assessed within the ECLS-K dataset using confirmatory factor analysis, which indicated good model fit for the SRS (Berry, Bridges, & Zaslow, 2004). The ECLS-K manual provides split-half reliabilities for the SRS subscales based on the full sample of children. Split half reliabilities for the Approaches to Learning and Self-Control measures were .89 and .79, respectively (NCES, 2001). Internal consistency was good for the Self-Control ($\alpha = .82$) and Approaches to Learning ($\alpha = .82$) subscales. Test-retest reliability from Fall to Spring is provided for the Approaches to Learning subscale only, which showed good reliability ($r = .77$; Berry et al., 2004).

Validity was also assessed within the ECLS-K sample by examining correlations between executive function measures and academic outcomes, two constructs shown to be related in previous literature (Blair & Diamond, 2008; Duncan et al., 2007). The Approaches to Learning measure of executive function was highly correlated with both teacher-reports (.51-.54) and moderately correlated with direct child assessments (.42-.45) of academic performance, indicating concurrent validity (Cohen, 1992; Rock & Pollack, 2002). The Self-Control measure was less-highly correlated with teacher reports (.26-.29) and direct assessments (.22) of academic performance, although these correlations were significant (Rock & Pollack, 2002).

Mathematics and Reading Achievement. Math and reading assessments were developed by experts in primary education for the ECLS-K study prior to the start of data collection. Items were designed to represent developmentally appropriate skills that aligned with both state and national standards (Pollack et al., 2005a). These assessments were administered in a one-on-one setting by trained assessors in kindergarten, 1st, 3rd, 5th, and 8th grades. Each assessment was designed to be representative of the math and reading skills that are needed for typical, grade-level curricula (Rock & Pollack, 2002). Assessments also contained items that overlapped with previous and subsequent assessments in order to aid in measurement of math and reading growth over time (Rock & Pollack, 2002). Data were collected for all children in the Fall of kindergarten and the Spring of kindergarten, 1st, 3rd, 5th, and 8th grades (Tourangeau et al., 2009). The current study uses these data to create growth models that serve as outcome achievement measures.

Math and reading assessments both have two administration stages. All children begin by taking a brief routing test containing items of varying difficulty. This routing test determines which of three forms will be administered for the second stage of the assessment. Based on routing test performance, children could receive a high level, middle level, or low level assessment (Rock & Pollack, 2002). Items overlapped across assessments, so the high level form contained some of the more difficult items from the middle and low level forms. This assessment design serves two purposes. First, it helps guard against floor and ceiling effects. Second, it allows for the use of Item Response Theory (IRT) scaling (Rock & Pollack, 2002). IRT was used to create a single scale for math assessments and a single scale for reading assessments so that scores could be compared across grade levels. Such vertically equated IRT scores are desirable when the goal is to measure growth over time (Grimm & Widaman, 2010). Such IRT scaling produces theta scores that can be used to assess reliability of assessment scales (Rock & Pollack, 2002)

Mathematics. The math assessment targets both conceptual and procedural math skills. The same math assessment was used in both kindergarten and 1st grade, with the majority of the questions focusing on basic number understanding and number operations. Questions were also included that touched on measurement; geometry and spatial sense; data analysis, statistics, and probability; and patterns, algebra, and functions (NCES, 2006). 3rd and 5th grade assessments focused on the same topics as the kindergarten and 1st grade assessment, but with questions scaled up to appropriate levels of difficulty (NCES, 2006). The 8th grade assessment touched on the same topic areas,

but differed from the elementary school assessments in that it placed a greater focus on more challenging items in the areas of geometry and spatial sense; data analysis, statistics, and probability; and patterns, algebra, and functions. These changes were meant to reflect changes in curriculum from elementary to middle school (Najarian, Pollack, & Sorongon, 2009). IRT scaled scores for the math assessment range from 0 to 174.

Internal consistency for the routing test and the individual forms was calculated using Cronbach's alpha. Reliability was acceptable for the routing test, ranging from .78 to .88 across time points. Reliability for the low form ranged from .66 to .78, reliability for the middle form ranged from .58 to .72, and reliability for the high form ranged from .73 to .83. The best estimate of reliability for IRT scaled scores is based on theta, and values indicated good reliability for the full reading assessment at all time points (.89-.97; Pollack, Atkins-Burnett, Najarian, & Rock, 2005b). Validity was evaluated by comparing the direct math assessment with teacher ratings of math ability during kindergarten and first grade assessments. Correlations were high (Cohen, 1992), ranging from .55 to .65 (Pollack et al., 2005a; Pollack et al., 2005b; Rock & Pollack, 2002), indicating good validity for this measure.

Reading. The kindergarten and 1st grade reading assessments were the same, and targeted basic reading skills such as letter identification and recognition and print knowledge, as well as receptive vocabulary and reading comprehension (NCES, 2006). The 3rd grade reading assessment added skills in phoneme awareness, as well as more complex items for word decoding, vocabulary, and reading comprehension (NCES,

2006). The 5th grade reading assessment included items from the third grade assessment, as well as questions addressing more complex levels of reading comprehension (NCES, 2006). The 8th grade reading assessment stressed reading comprehension, requiring children to respond to multiple passages of text (Najarian et al., 2009). IRT scaled scores for the reading assessment range from 0 to 212.

Internal consistency for the routing test and the individual forms was calculated using Cronbach's alpha. Reliability was good for the routing test, ranging from .75 to .88 across time points. Reliability for the low form ranged from .69 to .83, reliability for the middle form ranged from .70 to .84, and reliability for the high form ranged from .76 to .93. Reliability for the full reading assessment using theta values was good across all time points (.91-.96; Pollack et al., 2005b). Convergent validity was evaluated by comparing the direct reading assessment with teacher ratings of reading ability during kindergarten and first grade assessments. Correlations were high (Cohen, 1992), ranging from .62 to .72 across time points (Pollack et al., 2005a; Pollack et al., 2002b; Rock & Pollack, 2002), indicating good validity for this measure.

Demographic variables. Socioeconomic status (SES) is represented by a composite variable made up of parental education, parental occupation, and family income (Rock & Pollack, 2002). Gender information (male or female) was collected at the beginning of the kindergarten assessment window.

Data Analysis

In order to answer the research questions, analyses were performed in a Structural Equation Modeling (SEM) framework using AMOS software (Arbuckle, 2003). One set of data analyses was used to evaluate all the research questions.

Math and reading outcome data were collected at six time points. Unconditional latent basis growth curve analyses were first made to create two growth models (math and reading). These models were used to examine the structure of the growth. Latent growth curve models have a level and slope (initial starting point and growth over time, respectively) based on three or more data points (Singer & Willett, 2003). Level and slope for students' math achievement and level and slope for students' reading achievement were created using the six achievement measurement time points. Level indicates average math or reading achievement for all students in the Fall of kindergarten. Slope indicates the average change in math or reading achievement from kindergarten to 8th grade. Because previous research using the ECLS-K has suggested the growth in achievement may be non-linear (Grimm & Widaman, 2010; Roberts & Bryant, 2011) the four middle time points were allowed to vary. When these middle loadings (i.e., 'basis') are allowed to vary, these models are often referred to as Latent Basis Growth Curve models. By allowing these time points to vary, changes in children's achievement during elementary and middle school are more well represented.

In order to answer the four research questions, the two growth models were combined into a single SEM with the observed fine motor skill and EF variables added to the model as predictors of the latent level and slope variables for both math and reading

achievement. SES and gender were included in the model as control variables. See Figure 1 for the full model.

1. Do fine motor skills measured in kindergarten predict growth in children's math and reading achievement from kindergarten to 8th grade after controlling for socio-economic status, gender, EF, and math and reading skills measured in the Fall of kindergarten?

The data analysis plan described above was used to answer the first research question. The standardized coefficients for the paths from the fine motor variable to the math and reading latent growth variables were examined. If these paths were positive and significant, then the hypothesis that fine motor skills support growth in math and reading achievement was confirmed.

2. Do executive function skills measured in kindergarten predict growth in children's math and reading achievement from kindergarten to 8th grade after controlling for socio-economic status, gender, fine motor skills, and math and reading skills measured in the Fall of kindergarten?

The data analysis plan described above was used to answer the second research question. The standardized coefficients for the paths from the EF variable to the math and reading latent growth variables were examined. If these paths were positive and significant, then the hypothesis that early EF supports growth in math and reading achievement was confirmed.

3. Are the associations between fine motor skills and executive function stronger for math than for reading?

The standardized path coefficients from fine motor and EF to the two latent growth variables were evaluated to determine if associations were stronger for paths to the math latent growth variable than the reading latent growth variable. I hypothesized that associations would be stronger for growth in math achievement than reading achievement, so if the path coefficients from the predictors to the math latent growth variable are larger than those from the predictors to the reading latent growth variable this hypothesis was supported. Because there is no significance test for such differences, conclusions will have to be based on visual comparisons alone.

4. Is the association between kindergarten fine motor skills and growth in math and reading achievement moderated by kindergarten executive function skills?

A multigroup analysis was conducted on the model described above to determine if the associations found were different for children with high or low EF skills. These groups were created using standardized values of the EF composite. Children who were one standard deviation or more above the mean for EF were placed in the high EF group and children who were one standard deviation or more below the mean were placed in the low EF group. As a result of this dichotomy, this analysis did not include all students in the sample, only those who were especially high or low for EF.

Multigroup analysis involves a series of steps that determine if various aspects of a model are different for two or more groups. The first step involves determining if the measurement model is the same across groups. In this case, if growth is the same for the high and low EF groups. If the measurement model holds and is not significantly different across groups, the next step involves looking at differences in parameter

estimates. In this case, the moderating effect of EF will be determined by looking at the differences in the parameter estimates for the pathways from the fine motor variable to the latent growth variables. Conversely, if the measurement model proves to be different across groups, this next step of examining parameter estimates is not carried out because growth itself varies based on EF. Should the multigroup analysis indicate non-significant differences in the measurement model, individual path coefficients are examined to determine which specific associations vary based on children's EF skills in kindergarten. A compensatory effect for poor kindergarten fine motor skills was hypothesized, and the accuracy of this hypothesis was determined by examining the path coefficients from fine motor skills to achievement growth in for the two EF groups.

RESULTS

Missing Data

As described above, children were excluded from the current sample if they had fewer than three math or fewer than three reading assessment time points. Data were coded as missing if an assessment was not administered, if children were non-responsive or indicated that they didn't know the answers (NCES, 2006). Higher percentages of missing data were present for measures completed in the Fall of kindergarten than those completed at other time points. T-tests were used to determine if there were significant differences on available variables for students who were and were not excluded from the current study based on missing data. Differences existed for SES, fine motor skills, and EF based on missing data. Although these differences were significant this may be due to the large sample size ($n = 21,260$), as the actual mean differences between scores were quite small (ranging from .13 to .35 on a 174 point math assessment and a 212 point reading assessment). Students who were excluded from the study due to missing achievement data had slightly lower fine motor skills and EF ratings at the beginning of kindergarten and were of marginally lower socioeconomic status than those who were included in the current sample. This suggests the possibility of differential attrition for students at greater academic risk in kindergarten. This should be kept in mind when considering generalizability of the results of this study.

Within this reduced sample, missing data ranged from 1% to 19%. Higher percentages of missing data were present for measures completed in the Fall of kindergarten compared to other time points. There were not significant differences in achievement performance based on missing data for the fine motor measure. However, there were some achievement differences based on missing EF data. Reading scores in 1st, 3rd, 5th, and 8th grades were an average of 2 to 4 points higher for students without missing EF data. Similarly, math scores in the Spring of kindergarten, 1st, 3rd, 5th, and 8th grades were 1 to 3 points higher for students without missing EF data. Although these differences are small, they do suggest differences within the current sample based on missing data. It appears that teachers were more likely to complete the SES rating scale for students who had slightly higher achievement scores. Missing data were accounted for by Full Information Maximum Likelihood (FIML) estimation procedures in AMOS. FIML is recommended as the desirable approach to handling missing data, as it produces less biased estimates than deletion or single imputation methods (Enders & Bandalos, 2001).

Exploratory Analyses

On average, students in this sample began kindergarten with an average fine motor score of 6 (out of 9) and an average EF score of 3.08 (out of 4). Mean level IRT math and reading scores increased from kindergarten through 8th grade (see Table 1 for descriptive statistics). Initial correlational analyses indicated that fine motor skills and EF have a small, but significant association with each other ($r = .26$). Both fine motor skills and EF were moderately correlated with achievement at all time points. Math scores were

moderately to highly correlated with each other across time points. The same was true for reading scores (Cohen, 1992; see Table 2 for correlations among all variables).

Comparisons of Chi-Square values were used to determine the best-fitting model. Fine motor skills and EF were correlated in the initial model. The addition of correlations between the predictors and the two covariates (gender and SES) also improved model fit, $\chi^2(4) = 859.50, p < .01$. Error terms for the math and reading indicator variables were then correlated with each other at each grade level, resulting in additional improvement to model fit, $\chi^2(6) = 3,172.20, p < .01$. Although autocorrelation of errors is a problem for some analyses, this is not the case when modeling growth in SEM. In fact, it is desirable to correlate error terms when these correlations are theoretically based and result in an improved model fit (Grimm & Widaman, 2010). In the case of the current sample, correlated errors significantly improved model fit. These correlations could be attributed to changing assessors at different waves of data collection, to developmental changes in reliability of achievement measurement as children got older, or to some event that happened during a particular measurement year.

Based on the above adjustments to the model, final model fit was acceptable, $\chi^2(83) = 9,844.15, p < .01$. It is important to use other indices of model fit in addition to Chi-Square (Bryne, 2001), so Comparative Fit Index (CFI), Normed Fit Index (NFI) and the Root Mean Square Error of Approximation (RMSEA) were also examined. For CFI and NFI, model fit values above .90 are considered good, while model fit values below .10 are considered good for RMSEA (Fan, Thompson, & Wang, 1999). The current model

had a CFI value of .92, a NFI value of .92, and a RMSEA value of .11, indicating acceptable model fit.

There was significant growth in both math and reading. The slope values were set to vary between the first time point at the beginning of kindergarten (latent basis = 0) and last time point in the spring of eighth grade (latent basis = 8). The parameters in-between were allowed to be estimated which allows for the model to account for non-linear growth in achievement. The slope and level intercept values and slope coefficients were used to plot the shape of growth for both math and reading. Growth in math performance was steepest from kindergarten to 5th grade and then tapered off somewhat in middle school (see Figure 2). Children made the greatest gains in the beginning of their academic careers, and while these gains continue in middle school, progress was not as rapid as it was in earlier grades. Growth in reading performance was steepest from kindergarten to 3rd grade. There was a slight decrease in the rate of these gains from 3rd to 5th grade, and then another decrease in the rate from 5th to 8th grade (see Figure 3). Hypotheses about these growth patterns are included in the discussion section.

The correlation between level and slope for math achievement was positive, indicating that overall, children who started kindergarten with higher math scores also show steeper growth in these skills through 8th grade. In this case, those who start higher are at an advantage and continue to show associated gains in math achievement. Conversely, the correlation between level and slope for reading achievement was negative indicating that overall, children who started kindergarten with lower reading

skills have somewhat steeper rates of growth in reading achievement through 8th grade. In this case, those who start lower have more room to make gains.

Main Effect of Fine Motor Skills

As hypothesized, children's fine motor skills at kindergarten entry were significantly associated with their growth in both math and reading achievement through 8th grade after controlling for gender, SES, EF, and math and reading performance in the Fall of kindergarten. Higher kindergarten fine motor skills were related to Fall kindergarten achievement scores for math ($\beta = 0.32, p < .001$) and reading ($\beta = .20, p < .001$), such that higher fine motor skills at kindergarten entry were also associated with higher achievement performance at the same time point. There was also a positive relationship between fine motor skills and growth in math ($\beta = 0.25, p < .001$) and reading ($\beta = 0.20, p < .001$), such that children who started kindergarten with higher fine motor skills also showed steeper rates of growth in achievement (see Table 3 for path coefficients). Overall, higher levels of fine motor skills at kindergarten entry were associated with higher concurrent achievement, as well as greater rates of growth in achievement.

Main Effect of Executive Function

As hypothesized, children's EF skills at kindergarten entry were significantly associated with math and reading achievement through 8th grade after controlling for gender, SES, and fine motor skills. Higher kindergarten EF skills were associated with math ($\beta = 0.23, p < .001$) and reading ($\beta = 0.17, p < .001$) achievement at kindergarten entry, such that children starting school with better EF skills had associated better math

and reading skills than their lower EF peers. Additionally, early EF skills were associated with steeper rates of growth for math ($\beta = 0.17, p < .001$) and reading ($\beta = 0.18, p < .001$), such that higher EF at kindergarten entry was associated with increasingly higher gains in math and reading achievement through middle school (see Table 3 for path coefficients). Overall, higher levels of EF skills at kindergarten entry were associated with higher concurrent achievement, as well as greater rates of growth in achievement.

Differential Associations for Math and Reading

An examination of standardized path coefficients shows a slightly larger association between fine motor skills and achievement for growth in math versus reading achievement. As hypothesized, higher early fine motor skills were related to significantly steeper growth in both areas, but this standardized value was somewhat larger for math ($\beta = 0.25, SE = 0.01$) than for reading ($\beta = 0.20, SE = 0.02$). However, standardized path coefficients from EF to slope for math ($\beta = 0.17, SE = 0.05$) and reading ($\beta = 0.18, SE = 0.06$) were nearly identical (see Figure 4). Unfortunately there is no significance test that can be used to determine if either of these differences is significant. The math and reading assessments are not on the same scale, so they must be compared using standardized values (β). The unstandardized values needed to make such a comparison are not appropriate in the current analyses. Therefore, these conclusions are based on a visual examination of the standardized coefficients.

Although the seemingly stronger association with math achievement slope was only present for fine motor skills, both fine motor and EF were more strongly linked to the latent math level variable than the latent reading level variable. However, as they

progress through elementary and middle school this difference persists for fine motor skills only, not for EF. This is similar to the associations between kindergarten math skills and growth in these skills through middle school – strong early math performance is associated with steeper rates of growth in these skills (level and slope are positively correlated).

Interaction between Fine Motor Skills and Executive Function

The high and low EF groups excluded children who were within one standard deviation of the mean for the EF composite variable. The low EF group contained 1,597 students ($M = 2.19$, $SD = 0.25$). The high EF group contained 1,711 students ($M = 3.84$, $SD = 0.12$).

The first multigroup test assessed for significant differences in the growth models across the two groups. The significant chi-squared test indicated that these two groups had different rates of growth ($\chi^2(8) = 431.42$, $p < .01$). Because of this difference in growth for the two groups, comparing path coefficients would not answer this question. In other words, growth is different depending on level of EF (as seen in Figures 4 and 5) so making comparisons to growth that is different is not very instructive.

Despite these differences, we examined the unconditional multigroup models, which allowed for the differences in growth based on EF group. A visual comparison of path coefficients was made across the two models, bearing in mind that the outcomes are slightly different because the latent growth models have different loadings. Although these comparisons do not take the place of a significance test and should be interpreted

with caution, they still offer some indication of potential differential associations between fine motor skills and achievement based on EF group membership.

A comparison of the path coefficients from fine motor skills to the latent slope and level variables suggests that EF does not moderate the association between fine motor skills and achievement. Standardized coefficients from the fine motor variable to the latent math slope were nearly identical for the low EF ($\beta = .61$) and high EF ($\beta = .62$) groups. Coefficients for growth in reading were also very similar for the low EF ($\beta = .63$) and high EF ($\beta = .66$) groups. These results do not support the hypothesized interaction between fine motor skills and EF (see Table 4 for coefficients for the two EF groups). However, these results do indicate that achievement growth looks different for children with different levels of EF, such that those with high EF make greater gains in both math and reading than those with low EF.

Examination of the growth parameters indicated that within the high-EF group, there was a slightly greater association between EF and the math level variable ($\beta = 17.11$) than in the low-EF group ($\beta = 15.81$). EF was more strongly associated with kindergarten math performance for children starting kindergarten with good EF skills. The high-EF group also had greater associations between EF and growth in math ($\beta = 13.15$) than the low EF group ($\beta = 10.53$; see Figure 5). Similarly, the high-EF group had higher reading scores in the Fall of kindergarten ($\beta = 28.09$) compared to the low-EF group ($\beta = 27.63$). The high-EF group also had steeper rates of growth in reading ($\beta = 16.02$) than the low-EF group ($\beta = 13.29$; see Figure 6).

DISCUSSION

The present study focused on the associations between fine motor skills, EF, and growth in children's math and reading achievement from kindergarten through 8th grade. While previous work has found associations between these constructs, findings have only extended through 5th grade, and have focused on individual time points, rather than on rates of change. This study incorporated 8th grade scores in order to gain a more thorough understanding of the relationship between children's early fine motor skills and executive function and their math and reading achievement. An interaction between fine motor skills and EF was also included to explore the associations between these two skills and later achievement.

Five major findings emerged from this study. First, the trajectory of children's growth in math and reading from kindergarten through the end of middle school is non-linear. Second, fine motor skills measured in the fall of kindergarten were significantly associated with children's math and reading from the start of Kindergarten through 8th grade. Third, EF skills measured in the Fall of kindergarten showed similar associations with children's math and reading starting levels and growth through 8th grade. Fourth, associations between fine motor skills and achievement appeared to be stronger for math outcomes than for reading outcomes, whereas this pattern was not the same for

associations between EF and achievement. Fifth, children's growth in math and reading achievement varies as a function of EF.

Growth in Math and Reading Achievement is Non-Linear

This study provides a more accurate understanding of how achievement changes throughout elementary and middle school than would have been gleaned from assuming linear growth, or from examining achievement at individual time points. Reading achievement grows steadily from kindergarten until 3rd grade, when there is a slight decrease in the rate of growth. There is another dip in the rate of reading growth in 5th grade as well. Math achievement grows steadily from kindergarten until 5th grade, and there is a decrease in the rate of growth through middle school.

The slowing of growth in reading achievement at 3rd grade may be due to the shift in reading instruction that occurs at this time. 3rd grade is usually when instruction focuses more heavily on reading to learn content, as opposed to the more foundational process of learning to read (Chall & Jacobs, 2003). This shift in reading instruction is thought to be the reason that some children begin to fall behind in reading beginning in the 3rd grade. This is also often the time when large gaps in reading achievement begin to emerge based on established early predictors of achievement such as SES (Chall, Jacobs & Baldwin, 1991). The reading assessment used by the ECLS-K also mirrors these changes, placing an increasingly heavier emphasis on reading comprehension as opposed to rote reading skills from 3rd grade forward (Tourangeau et al., 2009). Both the shift in instructional focus and the shift in testing focus may account for this slowing of growth in third grade.

The decreasing rates of growth occurring in middle school for both subjects are in line with previous findings about middle school achievement (Barber & Olsen, 2004). Research has established that children often show decreases in academic performance in middle school (Burchinal et al., 2008). This change has been attributed to children's changing perceptions of school, as many children report that they find the middle school environment to be less supportive and more difficult than elementary school (Boyd & Bee, 2011; Wentzel, 1998). For instance, in middle school children are more likely to report poor academic functioning as a result of the shift away from a single-classroom instructional model (Barber & Olsen, 2004), as well as more negative relationships with teachers (Wentzel, 1998). Additionally children often become less engaged in the learning process in middle school (Barber & Olsen, 2004), which may lead to a decrease in the rate of the gains they were making in previous years.

All of these factors may account for the decrease in growth seen after 5th grade in this study. As the school environment becomes more demanding children do not show the same steadily increasing rates of performance that were seen in earlier years. It is worth noting that the assessments used in the current study are not measures of actual school performance, so it cannot be said with certainty that these patterns of growth perfectly mirror those seen for children's actual school performance. However, the math and reading assessments are meant to capture the academic abilities needed for school success and to align with changes in curriculum across grades (Najarian et al., 2009; Tourangeau et al., 2009). Additionally, correlations between these achievement measures and teacher reports of student performance were high (Pollack et al., 2005a; Pollack et al., 2005b;

Rock & Pollack, 2002) suggesting that although there is not complete overlap with actual academic performance, these results are likely aligned with students' actual academic performance. Overall, despite these changes in achievement growth over time, fine motor skills and EF continue to be meaningful predictors of this growth through 8th grade.

Fine Motor Skills are Associated with Achievement

Fine motor skills measured in kindergarten were significantly associated with growth in math and reading achievement from kindergarten through 8th grade after controlling for gender, SES, EF, and early math and reading abilities. Previous research has found similar associations (Grissmer et al., 2010; Murrah, 20120), but the nature of these associations after elementary school was unknown. Additionally, studies have largely focused on examining single time points as a metric for longitudinal achievement, meaning that associations with actual rates of change were unknown. The current study not only links early fine motor skills to later academic performance, but demonstrates that children starting kindergarten with better fine motor skills show associated greater achievement gains than those starting with lower fine motor skills.

This finding underscores the importance of early fine motor skills in relation to achievement, as these abilities measured in kindergarten explained growth over eight years. These associations are likely due in part to the early associations between motor and cognitive development. These two skills share a similar developmental timeline and activate similar regions of the brain (Adolph, 2005; Diamond, 2000; Willingham, 1999), suggesting an overlap in functionality for these areas. Some researchers have suggested that early cognitive development is dependent upon early motor development, and

without strong early motor skills children are less likely to show associated early cognitive strength (Bushnell & Boudreau, 1993; Campos et al., 2000; Piaget, 1953). This association can also be seen in neuroimaging research, with improvements in brain functioning in areas that support complex and abstract thinking found as a result of motor activity (Leiner et al., 1991). The potential benefits of these early skills for cognitive development also result in improved later achievement (Cameron et al., 2012; Carlson et al., in press; Grissmer et al., 2010). The current findings expand this association through 8th grade, indicating that there are long-lasting and independent effects of these early skills.

The association between early fine motor skills and achievement may also be the result of cognitive load. Children with better fine motor skills are more easily able to participate in classroom lessons such as drawing a picture or copying letters and numbers, thus freeing up more cognitive resources to take in the actual lesson. For this reason, children with poor fine motor skills are likely to have more difficulty absorbing the information they are meant to learn in kindergarten. Such early deficits in learning result in children entering later grades without the foundational knowledge they need to succeed (La Paro & Pianta, 2000; Pungello et al., 1996). Furthermore, fine motor skills begin to stabilize in kindergarten (Son & Meisels, 2006), so the measures used in the current study are likely representative of children's later fine motor skills as well. Therefore, the same cognitive load issue described for kindergarten is likely to persist in later grades. If a child has difficulty with writing skills then taking notes during a lesson may require the allocation of resources away from the lesson itself. This potential explanation for the

association between fine motor skills and achievement has recently been supported in one other study linking these two constructs (Cameron et al., 2013).

Another potential explanation for this finding is school engagement and involvement. Children who have difficulty with fine motor skills in kindergarten are likely to struggle with classroom activities such as drawing, cutting with scissors, and building with blocks. Such activities are frequent in the typical early childhood classroom (Marr, Cermak, Cohn, & Henderson, 2000), so children who find these activities challenging may be less likely to enjoy being at school. This lack of enjoyment may result in less engagement and involvement in the learning process, which has been linked to poorer long-term achievement (Ladd & Dinella, 2009). This may be especially pertinent for growth through middle school, when decreases in rates of achievement growth have been attributed to an increasing lack of interest in participating in school activities (Barber & Olsen, 2004).

Executive Function is associated with Achievement

Executive function measured in kindergarten was significantly associated with growth in math and reading achievement from kindergarten through 8th grade after controlling for gender, SES, fine motor skills, and early math and reading performance. Children with greater EF skills in kindergarten show associated greater gains in achievement than those with lower EF skills. Previous research has found similar associations using other metrics for EF (Grissmer et al., 2010), but the nature of these associations beyond 5th grade was previously unknown. Additionally, there was little

understanding of the associations between EF and rates of change in achievement, as opposed to associations with achievement based on individual grades.

Neuroimaging studies have found overlaps in EF and cognitive performance (Diamond, 2000), particularly for unautomated cognitive tasks (Bush et al., 2000). As with the neurological link to fine motor skills, it may be that good EF skills are beneficial for cognitive development and associated later academic achievement. Cognitive load is also a factor when considering the association between EF and achievement. People have a limited amount of cognitive resources with which to complete various tasks. When tasks are difficult or unautomated they take up more of these resources, and when other factors in the environment distract from these tasks, an even greater number of resources must be used (Paas et al., 2004). Early EF is important component in allocating these resources appropriately. Children with poor EF are more likely to need to work harder to pay attention and stay on task (Blair & Razza, 2007; Paas et al., 2004), thus pulling cognitive resources away from classroom lessons. Self-control also plays a roll, as children who have difficulty controlling their behaviors and emotions are likely to have to expend more mental effort to act appropriately in the classroom environment, again taking away from the learning opportunities as hand.

Other components of early EF touched on in this study include learning independence and flexibility. These are both skills that contribute to academic success, as they are adaptive in a classroom setting (Miyaki et al., 2002). Children who are able to complete activities without the constant supervision and external motivation of a teacher are likely to be able to take in more information and capitalize on more learning

opportunities throughout the school day than peers who disengage when left to their own devices. The early skills measured in the current study not only prepare children for later grades by boosting their early academic performance, but also build the foundation for adaptive classroom behaviors later on. This is supported in the current study, where children with higher EF both started kindergarten with higher math and reading skills and also continued to grow in those areas more rapidly than those with lower early EF skills.

As with fine motor skills, early EF may also set the stage for later classroom engagement. EF has been linked to school engagement (Ladd, Birch, & Buhs, 1999), as children are more inclined to become disengaged at school if they are struggling to pay attention, stay on task, and control undesirable behaviors and emotions. Not only is learning itself more difficult in such a scenario, but social relationships are often negatively impacted by poor EF (Eisenberg et al., 2010), making the classroom a less happy place. Additionally, teachers often report less harmonious relationships with children who lack good self-control skills (Valiente et al., 2008), and positive student-teacher interactions play a large part in students' school engagement and academic success (Eisenberg et al., 2010; Ladd, 1990; Valienete et al., 2008).

Fine Motor Skills – but not EF – are More Highly Associated with Math than Reading Achievement

While associations between fine motor skills and achievement were all significant, standardized associations appeared to be larger for children's growth in math achievement compared to growth in reading achievement. As levels of early fine motor skills increased, children showed associated greater gains in math than reading through middle school. This association was likely the result of the links between fine motor

skills and basic math skills such as number knowledge, evidenced by activation patterns in the parietal cortex (Buetti & Walsh, 2009; Dehaene et al., 2004). Children learn about magnitude and size through interactions with the physical world, and number knowledge is linked to fine motor tasks that involve integrating visual input with motor output in this part of the cerebellum because an understanding of numbers needs to exist in the same cortical area as an understanding of general magnitude (Buetti & Walsh, 2009). Therefore, findings linking fine motor skills to cognitive development and achievement performance may explain the association between fine motor skills and overall growth in achievement, while stronger links to math achievement could be attributed to stronger associations rooted in early development at a neural level.

The finding that EF was not more strongly associated with growth in math than reading skills was unexpected. Previous research has found overlapping activation patterns in the brain for specific EF and math tasks (Blair & Razza, 2007; Houde et al., 2010), as well as findings linking EF more strongly to math than to reading within the ECLS-K dataset (Murray, 2012). There are three possible explanations for lack of differential associations with achievement growth in the current study. First, neuroimaging findings have focused on single tasks, while the current study uses a more comprehensive measure of math achievement that captures multiple components of mathematical knowledge. While such associations might be found with different components of math achievement such as comparisons of size and distance and basic numerical understanding (Houde et al., 2010), this is not the case when looking at a more global measure such as the one used in the current study.

Second, a previous study using the ECLS-K dataset examined links between EF and achievement only used the Approaches to Learning subscale of the SRS to measure EF (Murrah, 2012), while the current study used both the Approaches to Learning and Self-Control subscales. Although the inclusion of self-control is more representative of the EF construct as a whole (Blair, 2002; Blair & Diamond, 2008; Graziano et al., 2007; McClelland et al., 2006), it may be that the elements of EF captured by the Approaches to Learning subscale (attention, task persistence, learning independence, and flexibility) have a larger association with math than with reading, in which case the addition of self-control may attenuate this relation.

Finally, another possibility is the extension of growth into 8th grade. Murrah (2012) examined achievement through 5th grade only. As established above, many changes occur during middle school, including changes in curriculum, school environment, and cognitive ability (Barber & Olsen, 2004; Burchinal et al., 2008; Midgley et al., 1995). The current study also establishes that the trajectory of children's growth in achievement also changes during this time period, becoming less steep than it was during elementary school. The similarity for math and reading achievement in their associations with EF found here may be the result of these changes. As children progress in school there is a movement away from rote types of learning and a heavier focus on academic tasks that involve abstract thought and require multiple steps to complete, such as complex algebraic equations, multi-faceted reading comprehension questions, and reading itself (Pearson, 2009; Henry, 2007). EF involves primarily unautomated processes (Diamond, 2000), and such tasks are not likely to be fully or even partially

automated. This same changing pattern can be seen in the achievement measures used in this study. In particular, the 8th grade reading achievement assessment is weighted heavily toward reading comprehension problems. Perhaps as children get older math and reading begin to place a more similar demand on their EF skills, so the difference in these subjects seen in younger children fades away.

Growth in Achievement Varies Based on Executive Function

Children's growth in math and reading was different based on their early EF skills. Children who started kindergarten with low EF ratings not only had slightly lower achievement scores in the Fall of kindergarten than their higher-EF peers, but they also made slower academic gains through 8th grade. In other words, children with lower EF started behind their peers and then continued to fall farther behind with each progressing grade. This was true for both math and reading achievement.

These findings support the established positive association between early EF and growth in math and reading achievement. Children who have poor EF when they begin school are at an academic disadvantage throughout elementary and middle school (and likely beyond). These differences may be the result of the overlaps in brain function for early EF and cognitive development (Bush et al., 2000; Diamond, 2000). Children with strong EF skills may begin school with a cognitive advantage, aiding them in making strong gains throughout their academic careers. This group difference in growth may also be due to cognitive load, as having low EF early on means that children are lacking the skills needed for learning in the classroom environment (Blair & Razza, 2007). Either way, children who start school with lower EF skills are at a disadvantage. They appear to

be unable to catch up to those with higher EF, in fact falling farther and farther behind academically with each passing year.

LIMITATIONS

Despite the clear long-term association between fine motor skills and achievement, a causal relationship cannot be assumed in this study. Although these findings indicate a link from two early skills to later achievement, data were not experimental, so causality cannot be determined. Thus, it can only be concluded that these constructs are associated. Future research should examine this association using an experimental or quasi-experimental design.

An additional limitation relates to measurement. Although teachers' ratings of their students' EF skills provide valuable information, it would also be beneficial to have a direct assessment of these skills. Teachers may not always report accurately on all students; and direct assessment would minimize rater-error and potential bias in reporting. There is research that has used direct assessment of EF skills in association with fine motor skills (Cameron et al., 2012) to examine links with achievement, but it was not a longitudinal study. Future longitudinal research in this area would benefit from the inclusion of direct measures of EF.

A final limitation exists regarding generalizability of the results, as missing data were not missing completely at random. This missingness may be systematic in nature, as different trends were identified for children who were and were not missing data on outcome achievement measures as well as both predictors. Based on these patterns of

missingness, the current findings may not be applicable to some low-SES children, as well as those with slightly lower fine motor and EF skills. That said, differences in performance based on missing data, while statistically significant, were minimal. If anything, it may be that the impact of fine motor skills and EF on achievement were somewhat masked here due to the exclusion of these lower-performing fine motor and EF groups. The current results suggest that if these lower-performing children had been included, the positive associations seen with achievement growth may have been magnified. Additionally, children who were excluded from the study due to missing data differed from those who were included by less than half of a point on both a 174 point math and 212 point reading assessment. Overall, missing data analyses suggest that missing data is a marginal issue, but the potential systematic nature of this missingness should be kept in mind when considering what populations these results may generalize to.

IMPLICATIONS AND FUTURE DIRECTIONS

The current study expanded on knowledge about the associations between children's early fine motor and executive function skills and their growth in academic achievement throughout elementary and middle school. Previously there was little research that had looked at these associations beyond elementary school, even though middle school places very different academic demands on children. Additionally, there was little previous research that had examined associations with achievement in the context of academic growth. This means that the current study provides an understanding of how fine motor skills and executive function relate to rates of change in achievement.

Findings indicated that fine motor skills and EF measured in kindergarten continue to be positively associated with growth in children's math and reading achievement through 8th grade. Such information not only underscores the long-lasting association of these early skills with achievement, but also provides valuable information that can be used to improve targeted achievement interventions as well as furthering our understanding of childhood development overall. The extension of these findings into 8th grade bring up questions about potential interactions with school-level variables such as classroom climate, classroom quality, and school satisfaction and engagement – all things that tend to change during middle school. Although we now know that fine motor skills

and EF are linked to achievement during this time, it would be interesting to understand how this association is impacted by the changing school environment.

These findings also place a renewed emphasis on the importance of early interventions for these skills. Although elements of fine motor skills and EF are included in many of the daily activities in a classroom, these skills are not taught directly in schools. However, both have been part of more recent targeted interventions for children prior to elementary school (Diamond, Barnett, Thomas, & Monroe, 2007; Mashburn & Cottone, 2011). In order to further refine potential interventions, it would be useful to have a better understanding of which explicit components of achievement would benefit most from a targeted fine motor or EF intervention. For example, the current findings regarding differential associations with math and reading achievement suggest that fine motor skills may be most helpful for children struggling with math performance. The current study also reinforces the potential long-term benefits of such interventions. Therefore, children struggling with their fine motor and EF skills prior to entering elementary school should see long-term academic benefits of such interventions.

The association with growth in achievement found here also suggests that these two non-academic skills should be included more explicitly in early childhood curricula in general. The associations between these skills and achievement were positive, so enhancing such skill in early childhood would be beneficial for children's achievement trajectories throughout middle school. However, the current study focused on broad math and reading outcomes. These outcomes were comprised of many different components of

broader achievement skills. Therefore, future research should examine associations between these two skills and more specific areas of math and reading achievement.

To my knowledge there were previously no large-scale longitudinal studies that had included such a comprehensive measure of EF, although research supports the fact that there are multiple important components of EF present in early childhood. Including a measure of this construct that taps into attention, self-control, learning engagement, and flexibility and independence in the classroom provides more accurate information about the positive association between EF and achievement.

Overall, improving understanding of how fine motor skills and EF relate to achievement has implications for educational practices and our understanding of early development in general. From a developmental perspective, the association between fine motor skills and achievement is a relatively new phenomenon (Cameron et al., 2012; Grissmer et al., 2012; Son & Meisels, 2006), and this study expands on this association by examining growth through 8th grade. Additionally, the long-term association of both fine motor skills and EF with achievement suggests that these two skills should be included more explicitly in early childhood curriculum. A heavy focus on the influence of these skills on achievement is relatively new, so a more accurate picture of how these skills influence growth in math and reading achievement through 8th grade is critical.

CONCLUSION

The current study added to knowledge regarding the association between children's early fine motor skills and executive function and growth in math and reading achievement from kindergarten through 8th grade. A large-scale, longitudinal dataset was used to create growth models for the two achievement domains and kindergarten fine motor skills and executive function ratings were found to be positively associated with growth in math and reading achievement. Better fine motor and EF skills were related to increasing growth in achievement through elementary school. Links to achievement were greatest between math and fine motor skills, suggesting an especially strong tie between these two constructs. Additionally, a multigroup analysis indicated that growth in achievement differs for children with high and low executive function skills. The focus on outcomes through 8th grade offers new information about the strength of these associations through middle schools. These results expand on our general understanding of child development, as well as providing more specified information about how these non-academic skills can be used to improve children math and reading achievement.

Table 1. Descriptive statistics

Variable	<i>n</i>	%	<i>M</i>	<i>SD</i>	Min	Max
		Missing				
Gender		1%				
Male	4,831					
Female	4,715					
SES	9,285	3%	0.09	0.80	-4.75	2.75
FM	8,534	13%	6.00	1.98	0.00	9.00
EF	8,704	10%	3.08	0.57	1.00	4.00
F K Math	8,567	12%	27.07	9.34	10.51	93.23
S K Math	9,342	3%	37.69	12.12	11.57	112.51
S G1 Math	9,335	3%	63.11	18.16	13.48	132.49
S G3 Math	9,261	4%	100.96	24.41	34.56	166.25
S G5 Math	9,197	4%	125.29	24.48	50.86	170.66
S G8 Math	9,223	4%	142.32	21.93	66.17	172.20
F K Reading	8,103	19%	36.05	10.12	21.07	138.51
S K Reading	9,020	7%	47.50	14.04	22.35	156.85
S G1 Reading	9,195	5%	79.32	23.85	24.63	184.05
S G3 Reading	9,217	4%	129.21	27.83	51.46	200.75
S G5 Reading	9,190	5%	151.91	26.13	65.03	203.22
S G8 Reading	9,165	5%	171.16	27.53	85.62	208.90

Table 2. Correlations among predictor and outcome variables

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Gender(Male)	-												
2	SES	.00	-											
3	FM	-.06*	.21*	-										
4	EF	-.20*	.17*	.26*	-									
5	F K Math	.01	.43*	.41*	.33*	-								
6	S K Math	.03*	.49*	.43*	.34*	.83*	-							
7	S G1 Math	.06*	.38*	.41*	.31*	.72*	.78*	-						
8	S G3 Math	.10*	.42*	.42*	.31*	.68*	.73*	.78*	-					
9	S G5 Math	.11*	.42*	.41*	.31*	.62*	.67*	.73*	.87*	-				
10	S G8 Math	.05*	.43*	.40*	.31*	.57*	.61*	.66*	.79*	.85*	-			
11	F K Reading	-.07*	.37*	.31*	.28*	.71*	.63*	.53*	.50*	.46*	.43*	-		
12	S K Reading	-.08*	.34*	.31*	.28*	.65*	.66*	.54*	.52*	.48*	.45*	.83*	-	
13	S G1 Reading	-.09*	.39*	.34*	.31*	.65*	.65*	.65*	.62*	.58*	.55*	.68*	.76*	-
14	S G3 Reading	-.08*	.46*	.36*	.33*	.62*	.63*	.64*	.73*	.69*	.66*	.54*	.57*	.72*
15	S G5 Reading	-.06*	.46*	.35*	.32*	.59*	.61*	.62*	.71*	.73*	.70*	.50*	.53*	.68*
16	S G8 Reading	-.09*	.45*	.33*	.31*	.52*	.53*	.55*	.64*	.67*	.73*	.43*	.45*	.56*

* $p < .01$

Table 3. Path coefficients and standard errors for fine motor skills and executive function predictors and reading achievement from kindergarten to 8th grade.

	Math Level (Fall K)		Math Slope		Reading Level (Fall K)		Reading
	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)
Gender	1.59(.17)	0.09*	0.80(.05)	0.17*	-0.60(.20)	-0.03*	-.08(.06)
SES	3.97(.11)	0.35*	0.83(.03)	0.28*	4.27(.13)	0.33*	1.27(.04)
Fine Motor Skills	1.49(.04)	0.32*	0.31(.01)	0.25*	1.04(.05)	0.20*	0.31(.02)
Executive Function	3.72(.15)	0.23*	0.72(.05)	0.17*	3.12(.18)	0.17*	0.95(.06)

* $p < .01$

Table 4. Path coefficients and standard errors for low and high executive function groups

	Math Level (Fall K)		Math Slope		Reading Level (Fall K)		Readin
	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)	<i>B</i>	<i>b</i> (SE)
<i>Low EF</i>							
Gender	7.93(.46)	0.28*	31.19(1.54)	0.34*	8.85(.55)	0.27*	33.67(2.0)
SES	1.70(.30)	0.10*	2.60(1.00)	0.05*	1.53(.37)	0.08*	2.69(1.37)
Fine Motor Skills	3.94(.08)	0.64*	12.09(.27)	0.61*	4.37(.08)	0.61*	17.24(.30)
<i>High EF</i>							
Gender	6.05(.58)	0.18*	10.93(1.05)	0.20*	3.08(.62)	0.09*	13.48(1.8)
SES	3.57(.37)	0.17*	4.07(.67)	0.12*	3.75(.40)	0.18*	5.76(1.17)
Fine Motor Skills	5.98(.11)	0.64*	9.71(.20)	0.62*	5.41(.06)	0.57*	19.02(.17)

* $p < .01$

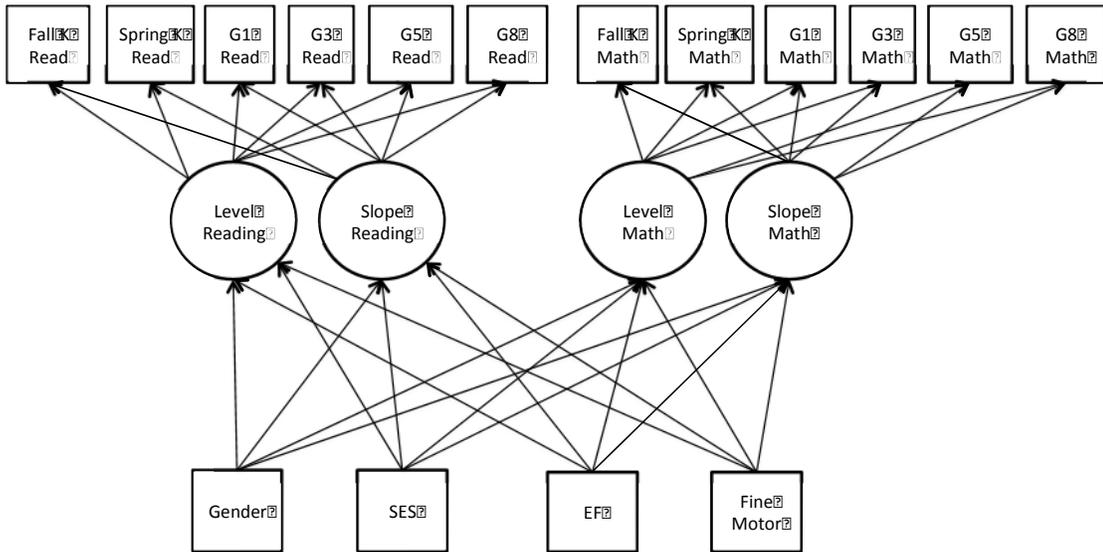


Figure 1. Full model of executive function and fine motor skills predicting growth in math and reading achievement.

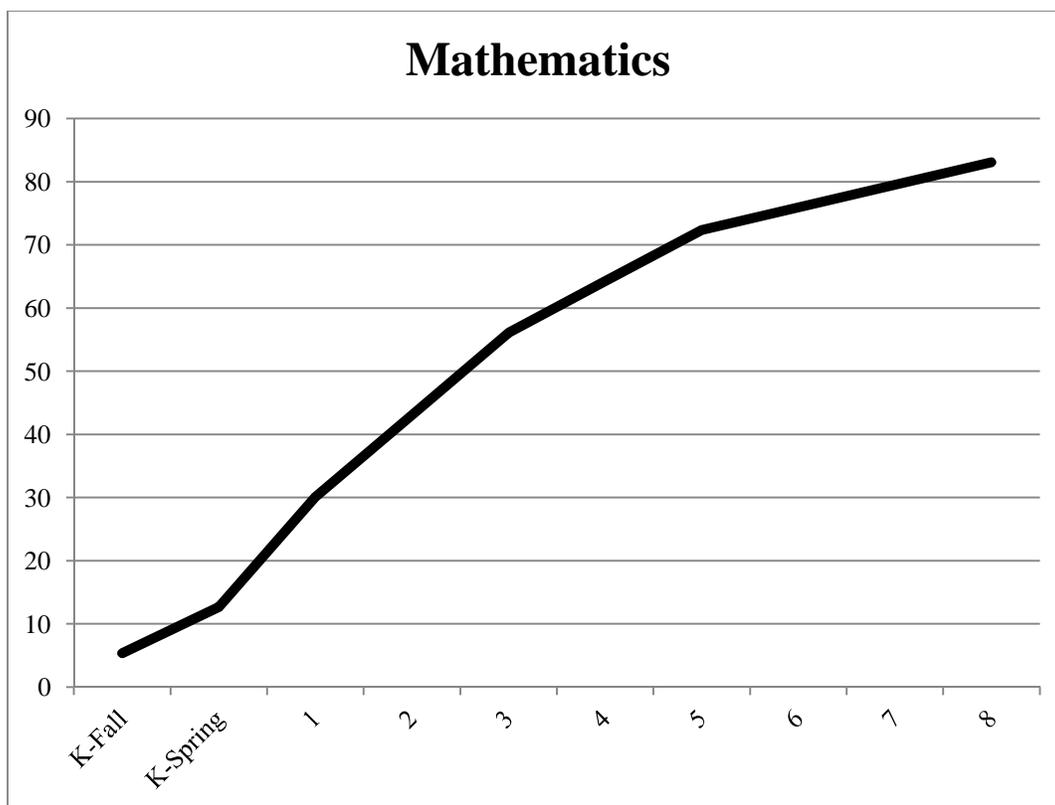


Figure 2. Non-linear growth in children's math achievement from kindergarten through 8th grade.

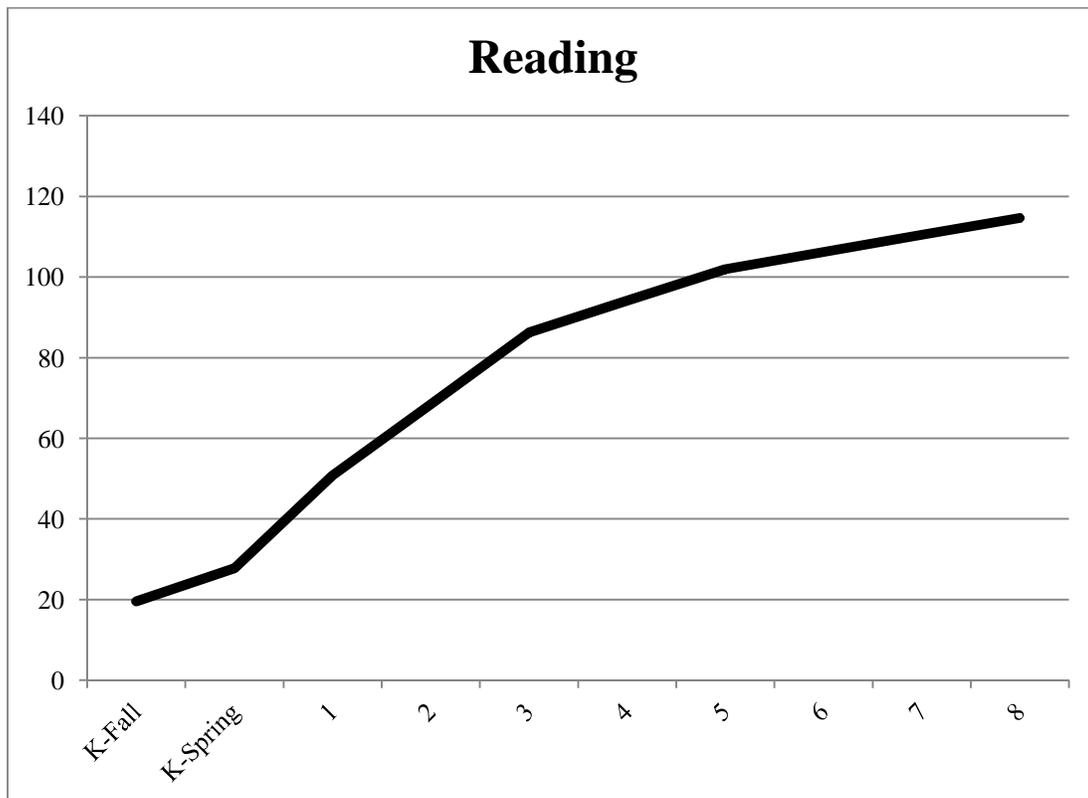


Figure 3. Non-linear growth in children's reading achievement from kindergarten through 8th grade.

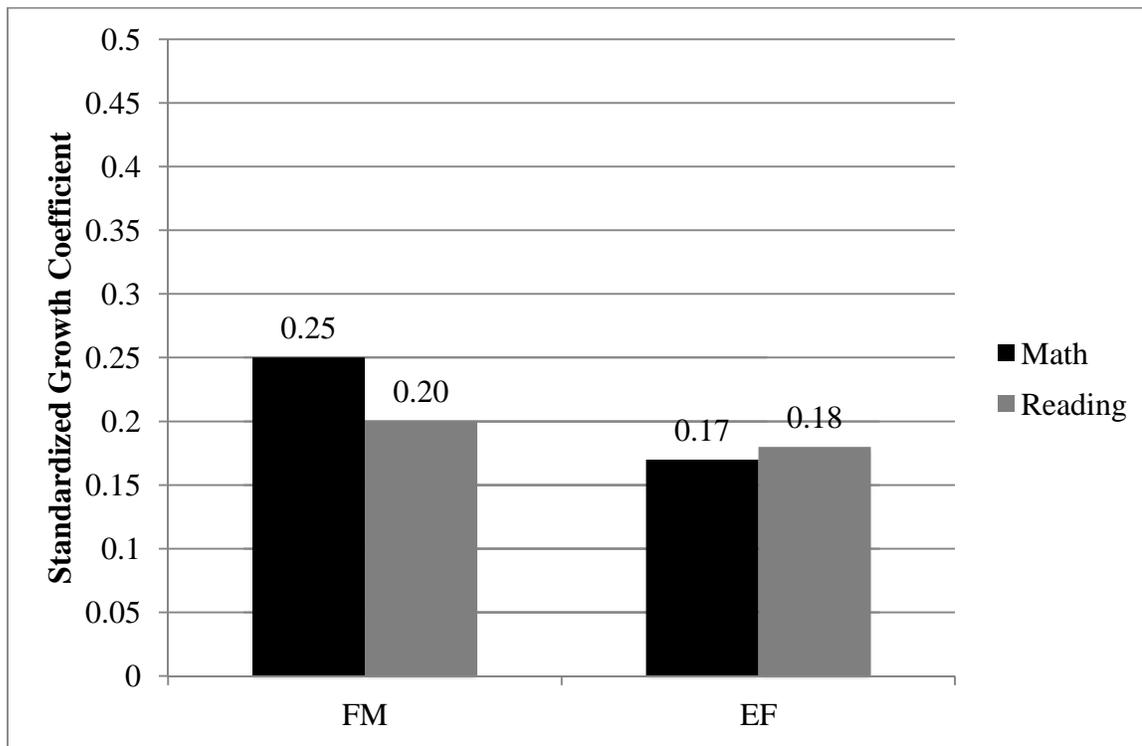


Figure 4. Comparisons of standardized path coefficients from fine motor and executive function predictors to growth in math and reading achievement.

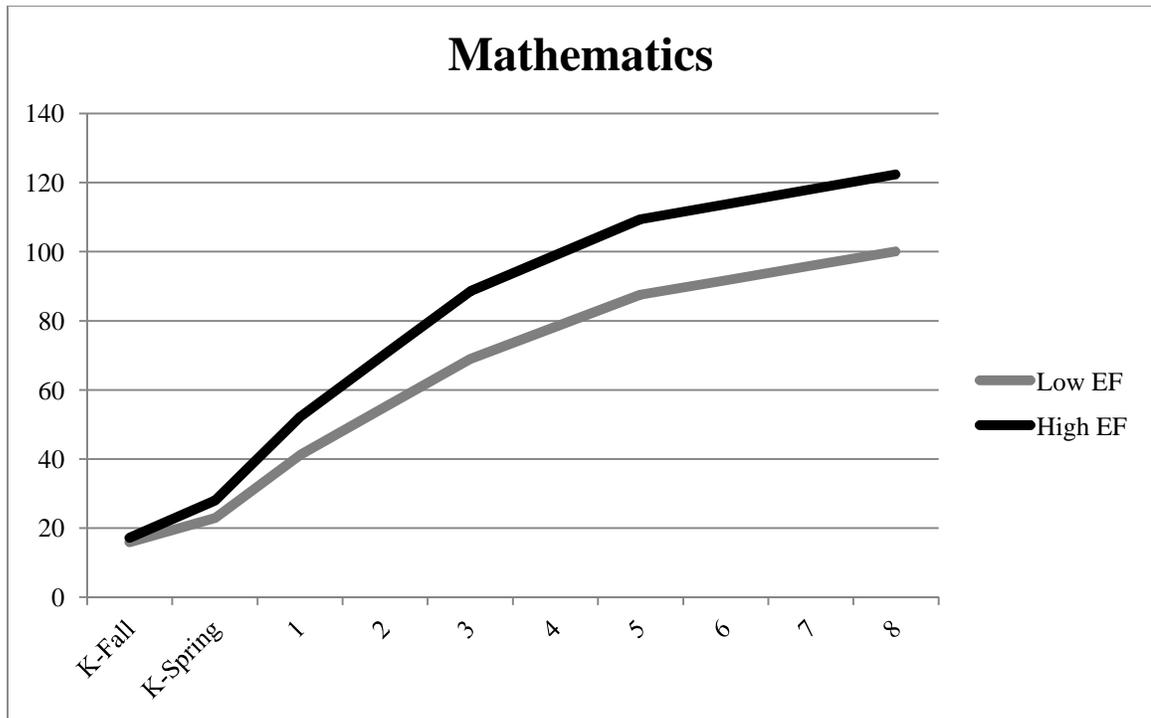


Figure 5. Comparisons of non-linear growth in math achievement for children starting kindergarten with low and high executive function skills.

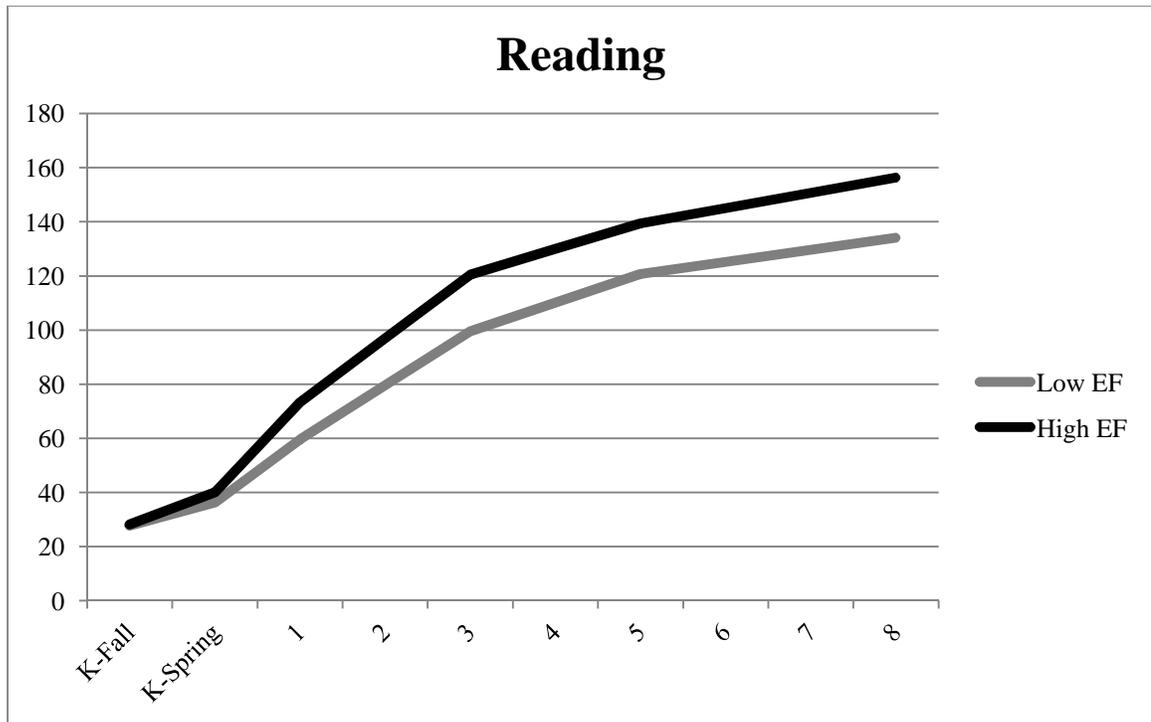


Figure 6. Comparisons of non-linear growth in reading achievement for children starting kindergarten with low and high executive function skills.

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