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RUNNING HEAD: EARLY MOTOR SKILLS, NUMERACY AND LITERACY

Fine motor and executive functioning skills predict math and spelling skills at the start of kindergarten: A compensatory account.

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Abstract

Research shows that executive functions (EF) and fine motor skills (FMS) contribute to early academic skills, possibly in overlapping ways. We examine whether and how EF and FMS interact in the concurrent prediction of math, reading and spelling skills at the start of kindergarten. Structural Equation Modeling (SEM) on data from 1248 5-year-olds support a compensatory account of EF and FMS in contributing towards math and spelling skills. Controlling for socio-economic status, age, time spent in kindergarten, and intelligence, the influence of EF on spelling achievement was larger for children with poorer compared to better FMS, and vice versa; FMS significantly predicted math achievement only in children with high but not low EF, and vice versa. Identifying EF or FMS difficulties at or before the start of kindergarten may be important. Different approaches to intervention involving EF and FMS may be appropriate for math versus spelling skills.We suggest for early childhood curricula to enhance opportunities for FMS development, especially for children who enter kindergarten with poor FMS.

Keywords: motor skills, executive functions, academic achievement, early childhood

Introduction

School readiness skills are important for subsequent academic achievement and attainment (Entwisle, Alexander, & Olson, 2005), providing children with the prerequisite skills to learn in a formal classroom context. While research on school readiness has traditionally focused on cognitive and behavioural skills (e.g., La Paro & Pianta, 2000), there is a growing interest in motor skills with several studies suggesting an association between fine motor skills (FMS) and academic outcomes in early childhood (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Pagani & Messier, 2012; Stoeger, Suggate, & Ziegler, 2013). Fine motor skills have been examined alongside executive functioning (EF) skills in several of these studies (e.g., Blair, Protzko, & Ursache, 2011; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Clark, Pritchard, & Woodward, 2010; Grissmer et al., 2010; Luo, Jose, Huntsinger, & Pigott, 2007; Pagani et al., 2010; Roebers et al., 2014). However, how FMS and EF interact to predict academic outcomes has not been extensively studied. Addressing this gap, the present study examines the interaction between FMS and EF in predicting math, reading and spelling skills at the start of kindergarten.

Fine motor skills and academic achievement in early childhood

Early FMS are commonly defined/assessed in terms of a child's ability to control and coordinate their hands and fingers in the manipulation of objects or tools, such as building a tower with blocks, using scissors, and drawing, writing, or copying with a writing utensil. Typically requiring close hand-eye coordination, FMS are also referred to as visual-motor, perceptual-motor, or psychomotor skills/integration (e.g., Cameron et al., 2015; Luo et al., 2007).

Fine motor skills are positively linked to academic achievement in childhood. Kulp (1999), for instance, found 7 to 9 year-old children's visual-motor integration skills to be related to teachers' ratings of their reading, math, writing, and spelling abilities. Longitudinal studies found FMS in early childhood (~ age 5) to predict later math and reading achievement (~ age 9 to 14), even after controlling for early math and reading abilities, and family and child characteristics (Grissmer et al., 2010; Pagani et al., 2010). Luo et al. (2007) found FMS predicted mathematics achievement over the course of kindergarten to the end of grade one.

There are a few propositions for the association between early FMS and academic achievement. One is that fine motor activities such as design/letter/number copying provide children with opportunities to practice mapping math and linguistic concepts to their visual representations (Cameron, Cottone, Murrah, & Grissmer, 2016). This view is consistent with constructivist theories of child development—for instance, of Jean Piaget—emphasizing that early learning occurs through the child's physical actions/interactions with the world (e.g., Santrock, 2017). Many learning tools or games for very young children—especially for early numeracy—tend to involve a child's fine-motor actions (e.g., counting, sorting, and matching) on manipulatives such as blocks or pegs. Luo et al. (2007) argues that children with better FMS are more proficient with manipulatives, form better mental representations of the objects being manipulated, and have better understanding of relevant concepts such as spatial relationships, which may contribute to mathematical learning and performance. Recent research also highlights the importance of representing numbers on one's fingers, such as in finger counting, as the mediating mechanism for the link between FMS and early numerical skill development (Fischer, Suggate, Schmirl, & Stoeger, 2018; Suggate, Stoeger, & Fischer, 2017).

Another is that the acquisition of math and literacy skills in early childhood invariably involves activities requiring FMS, such as copying and reproducing visual representations of math and language objects (e.g., letters, numbers, shapes, and lines). Studies examining subcomponents of FMS often find aspects such as fine motor writing and design copying to be more strongly related to reading and math achievement compared to other subcomponents such as fine motor manipulation (Cameron et al., 2016; Carlson, Rowe, & Curby, 2013). One suggestion is that children with, for example, stronger design copy skills may be able to learn (e.g., letters and numbers) and complete classroom tasks faster than children with weaker copy skills, allowing also for greater exposure to learning experiences (Cameron et al., 2012).

This account is consistent with the view that well-developed FMS free up cognitive resources for the material to be learnt or problem to be solved in academic tasks. Sweller's Cognitive Load Theory (CLT; Sweller, 1988; Sweller, Van Merrienboer, & Paas, 1998) and Ziegler's Actiotope Model of Giftedness (Ziegler, 2005, in Stoeger, Ziegler, & Martzog, 2008) emphasize the concept of the cognitive/mental load imposed by a task on the limited cognitive resource capacity of a learner. According to these theories, task performance requires the parallel execution of multiple subactions each competing for limited attentional, perceptual, and motoric resources. The automatization of subroutines (e.g., as schemas or action scripts) reduces the mental load or demands of the task on the limited capacity. For example, essential elements of finger-counting include: basic knowledge of the numbers involved, correspondence between number and finger representation, seriation, and fine motor control and coordination of the hands and fingers. In older children, these separate elements would have come to be incorporated within one schema (or script) for finger-counting and no longer need to be processed individually in working memory. Prior to this stage, each element yet to be automatized and assimilated into the schema will require substantial cognitive resources to be allocated for processing. Thus, for a child with more advanced FMS, an academic task may impose a smaller cognitive load compared to a child still struggling with fine motor control. Deficient subactions (e.g., fine motor skill of writing, in a math test) can divert cognitive resources away from other subactions (e.g., mathematical operations, in a math test).

Fine motor skills, executive functions and academic achievement in early childhood

Academic task performance thus seems to be influenced by the interplay between fine motor skills and cognitive—especially EF—skills. Executive functioning is commonly conceptualized as a multidimensional construct with three separable but related functions: updating/working memory (updating and monitoring of information), shifting/switching (switching between task/mental sets), and inhibition (suppressing irrelevant or prepotent information or responses) (Miyake et al., 2000). Following the maturation of the prefrontal cortex (PFC), EF continues to develop from early childhood into early adulthood (Diamond, 2002). Recent longitudinal studies have found that the three functions are not well-differentiated until children are around 15 years of age (Lee, Bull, & Ho, 2013). Across multiple studies, EF has been found to be characterized by a single factor in very young children (~2 to 6 years of age), and two factors (updating and inhibition-shifting/switching) in older children—with some ambiguity around the age of separation (see Lee et al., 2013). Executive functions in early childhood is often represented by child-friendly versions of tasks tapping into the respective functions of updating, shifting/switching, and inhibition, as well as more global measures that require a combination of the EF components (Garon, Bryson, & Smith, 2008). Other-rated (e.g., by parent, teacher, or day care provider) measures of child EF have also been used (e.g., Gioia, Isquith, Guy, & Kenworthy, 2000; Sherman & Brooks, 2010).

Research has consistently found EF to contribute to academic achievement in young children. For instance, Clark et al. (2010) found shifting, inhibitory control, and general executive behaviour measures at age 4 to predict children's mathematical achievement at age 6, even after controlling for general cognitive ability and reading achievement. Blair et al. (2011) found EF skills in preschool and kindergarten to predict early literacy. The authors also reported that when early literacy ability was controlled for, EF skills at the beginning of preschool predicted later literacy ability, with gains in EF predicting gains in literacy. Using a combined latent construct of EF, Roebers et al. (2014) found EF at preschool and at kindergarten to have a strong predictive relationship with later academic achievement at grade one, even after considering other predictors such as fine motor skills and intelligence. This relationship was also stronger for math than for literacy, consistent with other studies that have found EF to be more predictive of math than literacy in early childhood (e.g., Brock et al., 2009).

Research has also revealed a close relationship between early EF and FMS (Davis, Pitchford, & Limback, 2011; Grissmer et al., 2010). For instance, studies report an association between EF and motor coordination and movement (Diamond, 2000; Livesey, Keen, Rouse, & White, 2006; Roebers & Kauer, 2009). Motor deficits are also often found to co-occur in children with developmental disorders thought to be of a more cognitive nature, such as ADHD and dyslexia (see Diamond, 2000, for a review; Roebers & Kauer, 2009). Researchers suggest that some of the shared variance between motor and cognitive skills may be due to common processes underlying both skills, such as attention/EF, visual processing, fine manual control, and the ability to balance speed and accuracy demands (Davis et al., 2011; Roebers & Kauer, 2009). Researchers have also suggested that the overlap between EF and FMS may be understood in terms of common underlying neural mechanisms in the lateral cerebellum (Rigoli, Piek, Kane, & Oosterlaan, 2012), and to the close co-activation of the cerebellum and PFC, brain regions commonly associated with complex motor and cognitive skills (Diamond, 2000). The common involvement of the cerebellum, striatal, and cortical areas including the PFC in procedural learning is one reason proposed to underlie the often co-occurring motor and language difficulties in development (see Nicolson & Fawcett, 2011). As with motor skills, the cerebellum is ascribed a key role in linguistic skills and language-related tasks such as reading. Language disorders such as dyslexia have been proposed to arise from structural or functional cerebellar anomalies, such as with the neural circuit implicated in the procedural learning of language including the Broca's area, cerebellum, and PFC.

Interestingly, studies examining the relative importance of EF and FMS in predicting achievement have reported mixed findings with regards to the overlap between EF and FMS skills. On the one hand, supporting an overlap between the two skills, Roebers et al. (2014) found that FMS no longer predicted academic achievement (in mathematics, reading, and spelling) in early childhood after considering contributions from EF. On the other hand, studies have also found EF and FMS to independently predict academic skills and/or academic gains in young children, despite being correlated (Cameron et al., 2012; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014).

Another line of research has focused on the interaction rather than the overlap between FMS and cognitive skills and how this interaction predicts academic achievement. For instance, Stoeger et al. (2008) found the interaction between FMS and selective attention predicted academic achievement in a sample of gifted fourth-graders. Although the nature of the interaction was not clarified, a larger proportion of gifted underachievers were found to have both poor attention and poor FMS, compared to achievers. Recently, Cameron and colleagues (Cameron et al., 2015; Cameron et al., 2016) proposed that strong FMS may serve a compensatory mechanism in early learning. In a sample of 467 preschool children (2 to 5 years old), Cameron et al. (2015) examined whether visuomotor integration—a component of FMS, and the EF components of inhibitory control and working memory, predicted early language, literacy, and learning behaviour in an additive or interactive manner. Visuomotor integration was found to interact with inhibitory control in predicting children's performance in receptive and expressive language, phonological awareness, and learning behaviour at the start of preschool, as well as gains in print knowledge over approximately five months. The authors concluded that good visuomotor integration compensated for poor inhibitory control, and vice versa.

The theoretical and empirical findings thus far suggest that EF and FMS may interact to influence academic achievement in early childhood. The impact of poor EF on academic performance is expected to be smaller in children with more advanced FMS, as less EF needs to be spent on the motoric aspects and can be freed up for the academic aspects of the task. At the same time, a child with superior EF (but poor FMS) may have adequate cognitive resources to manage the academic demands of the task despite having to spend substantial resources fulfilling the motoric demands. Scant studies have probed the nature of this interaction to untangle the interrelated and overlapping contributions from FMS and EF to early academic achievement. Furthermore, EF and FMS may interact in different ways for different domains of academic achievement. As described earlier, EF has been found in some studies to be more predictive of math than literacy in early childhood (Brock et al., 2009; Roebers et al., 2014). Blair et al. (2011) argues this may be due to the different extent to which literacy skills draw upon frontal lobe and executive functions: early literacy tends to emphasize the acquisition of crystallized, factual knowledge in reading (e.g., vocabulary knowledge), whereas math and problem solving frequently requires more fluid reasoning and the processing of novel information. On the other hand, math and spelling tasks tend to contain more motoric elements or subactions and place stronger demands on FMS compared to reading. Thus, the degree to which EF and FMS contribute to an academic task likely depend on the interaction among EF and fine motor resources and demands.

The studies that have examined the interaction between EF and FMS are limited in their coverage of both predictor and criterion variables. For instance, Cameron et al. (2015) cautioned that though they found working memory to predict performance in an additive, rather than interactive manner, their working memory measure had limited variance and tapped only phonological (and not spatial) working memory. As the authors also pointed out, their single measure of inhibitory control was unlikely to have adequately captured the multi-faceted construct of inhibition, and they did not extend their investigations to math achievement. Including only single measures risks skewed findings due to the underrepresentation of complex constructs, along with known problems associated with task impurity (e.g., Miyake et al., 2000). Cameron et al. (2015) highlighted the need for future studies to consider math outcomes and comprehensive assessments of EF.

The present study

The present study examines the interaction between FMS and EF in the concurrent prediction of math, reading and spelling skills at the start of kindergarten. We hypothesize that, controlling for socio-economic status (SES), age, time spent in kindergarten, and intelligence, academic performance will be predicted by the interaction between FMS and EF. We expect this interaction to be more evident in early academic domains with higher EF and/or FMS demands, such as spelling and math, compared to reading. We further explore the nature of the interaction to examine the extent to which good FMS (or EF) compensates for poor EF (or FMS). On the one hand, good FMS may compensate for poor EF, such that the impact of (poor) EF on academic performance is attenuated in children with higher fine motor proficiency. On the other hand, good EF may buffer against the impact of poor FMS, such that the impact of (poor) FMS on academic performance is attenuated in children with higher EF. To address issues of coverage and task impurity in existing findings, we use a latent variable approach to obtain comprehensive measures of the multi-componential constructs of EF and FMS.

Analytic overview. As a first step, confirmatory factor analyses (CFA) will be performed to test whether the latent variables (FMS and EF) were described adequately by the observed variables. In separate structural equation models (SEM) for math, reading, and spelling, we examine the main and interaction effects of EF and FMS in predicting early academic skills. EF, fine motor, and academic skills are also regressed on four control variables: children's non-verbal intelligence, SES, age, and time spent in kindergarten.

Methods

Participants and design

Data used in this study were from a larger study examining the impact of early childhood classroom environments on child development and learning. Children were recruited from kindergartens across Singapore. The sampling locations were situated in areas with a good mix of kindergartens run by the four main service providers (Ministry of Education, government subsidized providers, private not-for-profit, and private for-profit centers). In Singapore, kindergartens provide half-day programs with a typical program length of 3 to 4 hours.

Parents of children in the participating centres were invited to participate in the study on a voluntary basis. The initial sample comprised 1278 children, but 30 children withdrew from the study. The final sample used in this study comprised 1248 children (49.2% boys) attending 60 kindergartens. The average age of the sample was 57.4 months (*SD* = 3.88 months). There were

59.0% Chinese, 11.1% Malay, 18.7% Indian, and 4.5% identified as others, which approximates the ethnic distribution in the population. The remaining 6.7% did not provide ethnicity information. Approximately 35.1% of our sample came from families with monthly household incomes equal to or larger than the national median range (7.9% of the sample did not provide income information). In terms of mother's educational attainment, 11.8% was below secondary, 9.9% was secondary, 1.4% was post-secondary (non-tertiary), 22.0% had a diploma or professional qualification, and 47.3% was university or above (8.6% did not provide information about mother's education). Parental consent and child assent were obtained before data collection. Ethics approval was obtained from the authors' university institutional review board.

Materials

Fine motor skills. The Brigance Inventory of Early Development III – Standardized (IED II; French, 2013) is a norm-referenced tool that measures children's developmental and learning skills from birth to 7 years of age across five domains. The Fine Motor subscale within the Physical Development domain was used in this study. This subscale assessed eight skills (*Early Fine Motor Skills; Builds Tower with Blocks; Visual Motor Skills; Draws a Person; Prints Personal Information; Writes Numerals in Sequence; Prints Uppercase Letters in Sequence; Quality of Printing*). Each skill comprised several skill indicators arranged in increasing order of difficulty (see Table 1). Test administration began at an age-appropriate level recommended in the test manual. Children completed the tasks using their dominant hand and received a score of 1 for each skill indicator that they were able to perform. Assessment of a skill was terminated when ceiling and basal was established for that skill. To minimize participant load, all skills were assessed except for *Prints Personal Information* and *Quality of Printing*. The ability to write one's own name (*Prints Personal Information*) is typically considered interchangeably with the ability to write letters in isolation on request (Lonigan, Schatschneider, Westberg, & The National Early Literacy Panel, 2008), already assessed in *Prints Uppercase Letters in Sequence; Quality of Printing* required a large quantity of writing samples from participants, which we were unable to obtain. For analysis purposes, a fine motor latent variable was derived (see details in Results section) using children's raw scores on *Visual Motor Skills* (Cronbach's alpha = 0.55), *Draws a Person* (Cronbach's alpha = 0.61), *Writes Numerals in Sequence* (Cronbach's alpha = 0.61), and *Prints Uppercase Letters in Sequence* (Cronbach's alpha = 0.96).

[Insert Table 1 here]

Executive functions. For a more comprehensive measure of EF, we included three tasks that indexed children's working memory capacity, two tasks that indexed children's inhibition ability, and two tasks that indexed children's switching ability. We also included two complex measures of EF commonly used to index children's EF in the context of behavioural self-regulation. The dependent measures for all tasks were computed such that higher scores reflected better EF ability.

Working memory.

Backward Digit Recall task. Children listened to a series of numbers and they were required to recall the numbers in backwards order (modified from Pickering & Gathercole, 2001). Each block had six trials progressing from a block with two numbers to a block with seven numbers, resulting in a total of 36 trials. The total number of correct trials were recorded.

Lost Animals task. Children were asked to complete a processing task, followed by a memory recall task within each trial (modified from Law, Morrin, & Pellegrino, 1995). In the processing task, children verified the accuracy of an addition equation in which two line matrices were added together to form a third line matrix (the processing task). Each line matrix consisted of five objects in a square (one at each corner and one in the middle), with a line connecting the objects in a variety of configurations. The objects in the matrices were presented as food or toys, and the lines depicted the paths taken by an animal to get food or toys. Following the processing task, children were instructed to recall the location of a coloured object (the target object) in the third matrix. Each block had six trials progressing from a block with one matrix to be verified and one location to be recalled to a block with three matrices to be verified and three locations to be recalled. In total, the task has 18 trials. The total number of positions recalled in the correct serial order was recorded.

Animal Updating task. Children were presented with pictures of animals one at a time on the computer screen. They were required to recall the identities of a specified number of animals (1, 2, 3, or 4) at the end of each trial (modified from Miyake et al., 2000). Children were not told the number of animals that would be presented on each trial to ensure that updating was being used in this task. The number of animals presented was varied randomly across trials (Min = 2, Max = 7). There were a total of four blocks of nine trials each, resulting in a total of 36 trials. In the easiest trials, children were required to recall the last animal presented; in the most difficult trials, the last four. The total number of animals recalled correctly were recorded. Cronbach's alpha for this task was 0.92.

Inhibition.

*Flanke*r task. Children were presented with a row of five arrows facing either left or right with the target arrow in the centre of the computer screen (modified from Kopp, Mattler, & Rist, 1994). The target arrow appeared on its own (neutral condition) or were flanked on either side by two arrows facing the same or the opposite direction (congruent and incongruent conditions, respectively). In each trial, children were asked to identify, by key press, the direction the target arrow was facing. The first block consisted of 28 neutral trials, followed by two pure blocks of 28 congruent, 28 incongruent trials, or vice versa to counterbalance possible order effects. In total, the task has 84 trials. The total number of correct responses in the congruent and incongruent conditions were recorded. Cronbach's alpha for the congruent and incongruent trials were 0.82 and 0.89, respectively.

Simon task. Children were presented with a fixation point in the centre of the computer screen, followed by either a frog or a butterfly (modified from Davidson, Amso, Anderson, & Diamond, 2006). Children were asked to bring the animal home safely by pressing the correct key (as labelled on the keyboard). In the congruent condition, the animals appeared on the same side as the location of the correct response key on the keyboard. In the incongruent condition, the animals appeared on the opposite side of the location of the correct response key. Children completed 30 congruent, followed by 30 incongruent trials, or vice versa to counterbalance possible order effects. In total, the task has 60 trials. The total number of correct responses in the congruent and incongruent conditions were recorded. Cronbach's alpha for the congruent and incongruent trials were 0.89 and 0.86, respectively.

Switching.

Dimensional Change Card Sort task. Children were instructed to choose one of two pictures at the bottom of the computer screen that matched the shape or colour of a target object presented at the top of the computer screen (adapted from the NIH Toolbox; Slotkin et al., 2012). Oral and visual cues were provided in each trial. Children were assigned to the "Shape first" condition or the "Colour first" condition to counterbalance possible order effects. In the "Shape first" condition, children first completed a "match by Shape" practice block, followed by a "match by Colour" practice block. The converse is true for children in the "Colour first" condition. Following the practice blocks, children were presented with a Pre-Switch block, where they were given the same task rule as the preceding practice block. This was then followed by a Post-Switch block, where the children were presented with a different task rule from the Pre-Switch block. Lastly, the children completed two Mixed blocks, in which the "Shape" and "Colour" rules were intermixed. Each Mixed block comprised 30 trials, where the Shape rule predominates (23 out 30 trials per block). A combined accuracy and reaction time score was calculated according to the formulae provided in the NIH Technical Manual. Based on accuracy data, Cronbach's alpha for the switch and non-switch trials were 0.63 and 0.94, respectively.

Picture-Symbol task. Children were presented with a bigram consisting of a picture (animals or vehicles) and a symbol (numbers or letters) on the computer screen (modified from Miyake et al., 2000). These bigrams appeared in one of the four quadrants on the screen. When the bigrams appeared in the top left and right quadrants, children were required to identify if the symbol in the bigram was a number. When the bigrams appeared in the bottom left and right quadrants, children were required to identify if the picture in the bigram was an animal. Oral cues were provided in each trial. Children first completed a pure Number block (19 trials), followed by a pure Animal block (19 trials), or vice versa to counterbalance possible order effects. These were followed by two Mixed blocks (29 trials each), in which children were presented with bigrams appearing in all four quadrants, one a time, following a clockwise order. Each Mixed block comprised 15 trials involving a rule switch (Animal/Number) from the previous trial, and 14 trials without a rule switch. Two dependent measures were derived from data in the Mixed blocks: (1) the ratio of total correct responses in non-switch trials to the number of items in non-switch trials, and (2) the ratio of total correct responses in switch trials to the number of items in switch trials. Ratio measures were used due to the unbalanced number of switch and non-switch trials. Based on accuracy data, Cronbach's alpha for the switch and non-switch trials were 0.80 and 0.83, respectively.

Complex EF measures.

Heads-Toes-Knees-Shoulders (HTKS). This task requires a combination of working memory, inhibitory control, and attention, and taps children's ability to regulate their behavior (Ponitz et al., 2008). Form A of its two parallel forms was used. Children were presented with behavioural rules where they were required to do the opposite of what the experimenter asked them to do. For example, if the experimenter instructed children to touch their head, children were required to touch their toes instead. The task has three parts, each comprising a set of behavioural rules and practice items. In Part One, children completed six practice trials with feedback about two rules (i.e., *touch your head/touch your toes*), followed by ten test trials. In Part Two, children completed five practice trials with feedback about two new rules (i.e., *touch your shoulders/touch your knees*), followed by ten test trials combining the rules from Part One and Two (i.e., *head/toes, knees/shoulders*). In Part Three, the rule pairs were switched (i.e., *heads/knees, shoulders/toes*). Children first completed six practice trials with feedback, followed by ten test trials. The task was discontinued if the child's total score on the test trials for Part One or Part Two was less than 4 points. The dependent measure was the total score across all three parts; a higher score reflects better task performance (Cronbach's alpha = 0.96).

Statue task. This task is a subtest from the NEPSY-II test battery requiring a combination of response inhibition and motor persistence (Korkman, Kirk, & Kemp, 2007). Children were required to stand like a statue holding a flag and to maintain this position for 75 seconds. During this time, the experimenter attempted to distract them using sound-based distracters (e.g., coughing, dropping a pencil). Each 5-second epoch was scored for eye movement, body movement, and vocalisation errors. A score of 2, 1 or zero was given for no errors, one error, and two or more errors, respectively. The total score was calculated by summing the scores for each 5-second epoch. Higher scores reflect better task performance. Cronbach's alpha for this task was 0.87.

Academic achievement. Three standardized subtests of academic achievement were administered. The Word Reading and Spelling subtests of the Wide Range Achievement Test – 4th Edition (WRAT-4; Wilkinson & Robertson, 2006) were used to assess children's early literacy skills. Word Reading measures letter (15 items) and word (55 items) reading, whereas Spelling assesses letter writing (13 items) and spelling of words (42 items). A reading score was derived by calculating the total number of correct responses on letter and word reading. A spelling score was derived by calculating the total number of correct responses on letter writing and word spelling. Higher scores reflect better reading and spelling skills. Cronbach's alpha for the Spelling (Letter Writing) subtest was 0.88. The Reading subtest has a reported Cronbach's alpha of .86 (Wilkinson & Robertson, 2006) and has been used in similar kindergarten studies in Singapore with an obtained alpha of .95 (Yeong & Rickard Liow, 2012)

The Test of Early Mathematics Ability – 3rd Edition (TEMA-3; Ginsburg & Baroody, 2003) comprised 72 items assessing children's informal and formal mathematics knowledge. Informal knowledge was measured through four categories of items: numbering (e.g., verbal counting by ones), number comparisons (e.g., choosing the larger number), calculation (e.g., addition of concrete objects), and concepts (e.g., number constancy). Formal knowledge was assessed via four categories: numeral literacy (e.g., reading or writing numerals), number facts (e.g., subtraction facts), calculation (e.g., written addition accuracy), and concepts (e.g., written representation of sets). Test administration began at an age-appropriate entry point recommended in the test manual and was terminated when ceiling and basal were established. Each item was scored dichotomously as 1 (if the scoring criteria was met) or 0 (if the scoring criteria was not met). An early numeracy score was derived by calculating the total number of correct responses on this task. Cronbach's alpha for TEMA-3 was 0.95.

Control measures. Children's non-verbal intelligence, age and time spent in kindergarten (at the first assessment date), and family's SES were used as control measures in this study. Non-verbal intelligence was measured using the *Raven's Coloured Progressive Matrices* (Raven, 1936). This task comprised three sets of twelve items (Sets A, AB, and B). Within each set, items were arranged in order of increasing difficulty. In each item, children were presented with a pattern in matrix format with a missing element. Children were asked to select the element that completed the pattern from a set of alternatives. The total number of correct responses across all three sets represented children's non-verbal intelligence score. Children's age at the first assessment date was calculated as the difference between their date of birth and the date of their first day of test administration. Similarly, the time spent in kindergarten was calculated as the difference between their first day in kindergarten and the date of their first day of test administration. A composite SES score was derived from a principal components analysis of four variables: mother's education, father's education, family income, and housing type. Housing type is a common indicator of SES in the Singapore context (e.g., Sabanayagam, Shankar, Wong, Saw, & Foster, 2007). It was classified as follows: (1) small size public apartments (1- to 2-room), (2) medium size public apartments (3-room), (3) large size public apartments (4-room), (4) large size public apartments (5-room or executive flat), (5) other types of public apartments, (6) private apartments, and (7) landed property (e.g., bungalow, semi-detached, terraced house).

Procedure

Assessments of children's FMS, academic achievement, EF, and non-verbal intelligence were conducted between February and September in their first year of kindergarten. These measures were administered to the participating children at their kindergartens as part of a larger task battery, by trained research assistants. The measures were divided into five sets, with each set taking 40 to 60 minutes to complete. Each task was administered individually to the child. Data was collected from each child over two days to several weeks, depending on the arrangements with each kindergarten. Information about the children's family background (i.e., family income, parents' education level, and housing type) were collected using questionnaires that were distributed to parents throughout the year.

Results

Confirmatory factor analyses

Fine motor skills. Of the six skills that were assessed, *Early Fine Motor Skills* (mean = 19.00, SD = 0.00) and *Builds Tower with Blocks* (mean = 10.76, SD = 0.87) showed little or no variation in our sample due to ceiling effects. Thus, these skills were excluded from the CFA. A 1-factor model comprising *Visual Motor Skills, Draws a Person, Writes Numerals in Sequence,* and *Prints Uppercase Letters in Sequence* provided reasonably good fit with the data (RMSEA = 0.060, CFI = 0.977, and SRMR = 0.043). All manifest variables loaded significantly on the latent variable (standardized factor loadings ranged from 0.43 to 0.82).

EF. We specified a 1-factor model comprising all nine EF measures. In addition, we followed Lee et al.'s (2013) approach of regressing the incongruent or switch measures to their congruent or non-switch counterparts to obtain a purer measure of the underlying EF construct. Although this model provided reasonably good fit with the data (RMSEA = 0.039, CFI = 0.978, and SRMR = 0.031), the manifest variables from the Simon and Picture-Symbol tasks showed inadequate loadings (standardized factor loading < 0.32) on the latent variable (Tabachnick & Fidell, 2001). The revised model, excluding these two variables, showed significantly improved fit (RMSEA = 0.032, CFI = 0.982, SRMR = 0.022). All seven manifest variables loaded significantly (standardized loadings 0.33 to 0.69).

Moderation analyses

Table 2 presents the descriptive statistics and the correlations amongst the study variables. All three academic achievement variables were strongly correlated with the EF and fine motor factors. Fine motor skills were most strongly correlated with spelling (r = .68) and least with reading (r = .53); EF was most strongly correlated with math (r = .65) and least with reading (r = .43).

[Insert Table 2 here]

We tested our SEMs with Mplus 7 (Muthén & Muthén, 1998-2012) using maximum likelihood estimation with robust standard errors. The criterion (math, reading, or spelling) and predictors (FMS and EF latents) in each analysis were also regressed on the control variables (non-verbal intelligence, age, time spent in kindergarten, and SES). Results of the SEMs for mathematics, reading and spelling are presented in Figure 1. After controlling for non-verbal intelligence, SES, age, and time spent in kindergarten, math was significantly predicted only by the interaction between EF and FMS (β = .06, p = .009) and spelling was significantly predicted by EF (β = .85, $p < .001$), FMS (β = 1.49, $p < .001$), and their interaction term (β = -.17, $p <$ .001). Reading was not significantly predicted by FMS, EF, nor their interaction term.

[Insert Figure 1 here]

To explore the nature of the interactions, we conducted tests of simple slopes for high and low FMS and high and low EF (at ±1 *SD* and ±2 *SD* from the mean). For math, the relationship between EF and math achievement was significant ($b = 1.43$, $p = .03$) only for children with very high FMS (2 *SD* above mean). Although none of the other simple slopes for FMS were significant, the general pattern suggests that the contribution of EF to math may be larger for children with better compared to poorer FMS (Figure 2a). The simple slopes for high EF were significant, suggesting that FMS significantly predicted math achievement only in children with high, but not in children with low, EF . Likewise, this relationship was stronger for children with higher EF (+2 *SD*: $b = 1.82$, $p = .003$ vs. +1 *SD*: $b = 1.47$, $p = .045$) (Figure 2a). For spelling, all simple slopes were significant ($p < .00$). Better EF/FMS was associated with higher spelling achievement at all levels of FMS/EF; the contribution of EF to spelling was larger for children with poorer compared to better FMS (from -2 *SD* to +2 *SD*: b = 3.17, 2.79, 2.02, 1.63), and the contribution of FMS was similarly larger for children with poorer compared to better EF (from -2 *SD* to +2 *SD*: b = 5.45, 5.06, 4.29, 3.91) (Figure 2b).

[Insert Figure 2 here]

Discussion

The present study investigated the interaction between FMS and EF in the concurrent prediction of math, reading and spelling skills at the start of kindergarten. Controlling for SES, age, time in kindergarten, and intelligence, we found evidence of an interaction for the domains of math and spelling. This is generally consistent with previous findings that found aspects of fine motor and cognitive skills to interact in predicting differences in children's academic achievement (Cameron et al., 2015; Stoeger et al., 2008). In addition, we extended previous findings by investigating the interaction in early academic skills, in a large, representative kindergarten sample, and in specific academic domains relevant to early childhood education. Previous findings by Stoeger et al. (2008) were based on a selected sample of gifted fourth graders' general scholastic achievement averaged over math, language, and science, while Cameron et al.'s (2015) findings were based on preschool children over a wider age range of two to five years, and excluded math outcomes. Despite some differences in the aspects of FMS and EF examined across the studies, the general finding is largely consistent with an interactive account of EF and FMS contributing to academic achievement.

Notably, our study shows that whether FMS and EF interact in predicting academic achievement depends on the domain of academic skills under consideration. Consistent with our expectations, we found the interaction to be more evident in spelling and math, compared to reading. This seems consistent with the view that early math and spelling skills may have greater demands on EF and FMS, compared to reading (Blair et al., 2011; Cameron et al., 2016). Blair et al. (2011) clarifies that although EF may play a role in the early stages of acquiring the knowledge required for reading (e.g., alphabetic, phonological, and vocabulary knowledge), once acquired, it is this crystallized knowledge, rather than EF, that will impact reading performance. On the other hand, the present study found strong main and interaction effects from FMS and EF to spelling performance. Spelling necessitates the writing of letters and may share some common variance with aspects of our FMS variable (i.e., the ability to print letters in sequence). The ability to write one's own name or letters on request has been identified in a set of large-scale meta-analyses as one of the precursor/early skills from preschool/kindergarten to consistently predict later (first grade and beyond) reading, writing, and spelling skills, even when controlling for other related predictors (Lonigan et al., 2008). However, although some shared variance with letter-writing may contribute towards these relationships, our FMS latent variable included several other non-literacy-related components. Some studies have proposed that graphomotor aspects of FMS may account for the relationship between FMS and emergent literacy skills (e.g., Suggate, Pufke, & Stoeger, 2018). The definition and assessment of FMS often include graphomotor skills—related to handwriting or drawing, and non-graphomotor skills (e.g., building towers with blocks). Suggate et al. (2018) found graphomotor, but not non-graphomotor, FMS to contribute significantly to early reading and letter naming in kindergarteners. However, their later study found a significant link between non-graphomotor FMS at kindergarten and reading at grade 1, which was not mediated by graphomotor skills (Suggate, Pufke, & Stoeger, 2019).

Spelling likely draws heavily on FMS in general, including dexterity in manipulating writing tools, and hand-eye coordination and visuomotor integration in reproducing symbols. Our finding that children with better FMS showed better spelling performance than children with poorer FMS provides support for this argument. Similarly, children with better EF showed better spelling performance than children with poorer EF, suggesting that spelling may involve high demands on EF for children in this age group. The relation of EF to spelling skills in early childhood is not well understood as spelling ability has rarely been examined in isolation, usually only as part of academic achievement or combined with reading or other literacy skills (e.g., Roebers et al., 2014). Findings from the present study suggest a very different pattern of contributions from EF and FMS to reading versus spelling achievement. Deficits in either EF or FMS may have greater impact on early spelling than reading performance. On the other hand, the pattern of the significant interaction suggests that good FMS may compensate for poor EF: spelling performance in children with better FMS were less affected by having poor EF than children with poorer FMS, and vice versa. The implications of a child having either poor EF/FMS may thus be less severe than if they were poor on both. Spelling is a key literacy skill (Lonigan et al., 2008) that is important for writing development (Abbott & Berninger, 1993; Graham & Harris, 2000). Given the different pattern of associations with EF and FMS, it may be worthwhile for more future studies to examine reading and spelling skills separately.

The pattern of interaction was slightly different for math achievement. Although EF and FMS were both highly correlated with math, when considered together while controlling for background variables, only the interaction between them significantly predicted math performance. This suggests that EF and FMS contribute in highly overlapping ways to math achievement. Furthermore, FMS significantly predicted math achievement only in children with high, but not in children with low EF, suggesting that the compensatory effects of FMS on math performance may only manifest above a certain minimum threshold of EF. As suggested by Blair et al. (2011) and corroborated by the strong correlation between EF and math in the present study (strongest among all three academic skills), early math may have such a high EF load that good FMS will not be sufficient to compensate for very low EF.

The different patterns of interactions suggest that different approaches to remediation may be appropriate for different academic skills. For instance, while spelling performance may possibly be improved by enhancing EF and/or FMS, a heavier focus on boosting EF skills may be required for math, especially for children with very low EF. Improving FMS may additionally benefit children with sufficiently high EF. Identifying whether children have EF or fine motor difficulties at or before the start of kindergarten may thus be important. Some evidence suggests that EF training in young children has beneficial effects on language and math outcomes (Blakey & Carroll, 2015; Goldin et al., 2014; Malekpour & Aghababaei, 2013). Less is known about the efficacy of FMS training. Hence, apart from intervention focused on subject-specific skills (e.g., training non-symbolic approximation for early math; Park, Bermudez, Roberts, & Brannon, 2016), future studies could examine the impact of EF and/or FMS interventions on early math and spelling achievement, with particular emphasis on FMS interventions targeted at children with poor EF or FMS at/or before the start of kindergarten.

The current findings should be interpreted with some caveats in mind. First, tests of simple slopes test for the significance of a predictor only at specific values of a moderator and may not apply to other values of the moderator. The pattern of results may vary if alternative values are chosen. Second, some have proposed that the observed relationship between FMS and academic achievement is mediated by EF. Stoeger et al. (2013) examined whether the relationship between FMS and math achievement was mediated by attention skills in 161 fourth-graders. Using a set of regression analyses, they found the effect of FMS on math achievement to decrease significantly when attention skills was controlled for. However, although the authors interpreted the findings as supporting a mediation account, mediation models require a strong theoretical model due to its inability to rule out equivalent and non-equivalent alternative models. In a non-experimental setting and with concurrently measured variables (as with Stoeger et al., 2013), it is difficult to ascertain the causal directions between the two predictors in the absence of precise theoretical prescriptions (Little, Card, Bovaird, Preacher, & Crandall, 2007). In the current consideration of EF and FMS, the argument that EF and FMS are both required and often co-activated in many EF and fine motor tasks (e.g., Cameron et al., 2016; Diamond, 2012) makes it difficult to specify one predictor or the other to the antecedent or mediating role.

Future studies can expand on current findings and examine causal mediations across development. Related to this point, while the current study examines a moderation model based on cognitive load theories, it is not meant to be a direct test of cognitive load models. Future studies can utilize an experimental approach to test if better FMS indeed frees up EF resources for better task performance—that is, if EF mediates the relationship between FMS and academic achievement.

Finally, we highlight certain limitations of the measures included in current analyses. Reading achievement was assessed with letter and word reading, which could be considered "lower-level" skills that are less demanding of cognitive competencies such as EF, compared to "higher-level" skills such as reading comprehension (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014). Studies with older children have found EF to contribute to reading comprehension and lower-level skills such as decoding in different ways (Arrington et al., 2014), and to contribute to reading comprehension but not word recognition after controlling for variables such as attention and decoding (Sesma, Mahone, Levine, Eason, & Cutting, 2009). Thus, current findings regarding the (lack of) involvement of EF in reading may be limited to letter/word reading, and may vary if reading comprehension is included. Similarly, although our FMS assessment included a mix of tasks, our latent variable eventually comprised only tasks involving graphomotor skills. Non-graphomotor FMS such as building towers with blocks can be argued to be purer indices of FMS compared to graphomotor tasks, which also involve proficiencies more directly relevant for academic tasks, such as knowledge/familiarity with numbers and letters, and competence with writing tools. As earlier discussed, the current relationship found between FMS and academic skills may partially be driven by these commonalities. It is thus possible that the involvement of FMS in early math and spelling skills—and consequently any related screening or remediation—may be limited to specifically graphomotor skills. Likewise, the lack of significant relationships observed between FMS and reading in our SEM might be due to the graphomotor-dominance of our FMS latent; recent studies suggest that early non-graphomotor FMS, rather than graphomotor skills, may be predictive of children's later reading skills (Suggate et al., 2019). Although non-graphomotor tasks were included in our test battery, they had to be excluded due to limited variance in the current sample. Future studies can include a broader range of non-graphomotor tasks to tease apart contributions from graphomotor and non-graphomotor skills.

With the afore parameters in mind, the current study provides support for a compensatory account of EF and FMS in early academic performance, as previously suggested by researchers such as Cameron et al. (2016). In addition, current findings refine the hypothesis with insights on how FMS and EF may compensate for each other in different ways for different academic skills. The use of multiple, comprehensive measures in a latent variable approach also addressed some of the limitations of previous findings related to possible biases arising from task or construct impurity. While the importance of EF in early education and development has attracted more attention in the recent years, our findings highlight the complementary importance of FMS, contributing directly to and also compensating for poor EF in some academic skills. It may thus be important for early childhood curricula to include increased opportunities for FMS training (at least in graphomotor skills), especially for children who enter with poor FMS (see also Cameron et al., 2012). Several countries, as well as the World Health Organisation, have physical activity and sedentary behaviour guidelines for children and adolescents, some including infancy, and the preschool years (see Parrish, Vella, Okely, & Cliff, 2014; Tremblay et al., 2012). Although these were largely motivated by concerns regarding physical health outcomes and involve mainly gross motor activities, guidelines for preschool children could possibly be extended to include FMS, given the renewed interest in and findings on the role of FMS in early childhood development.

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Figure captions

Figure 1. Structural equation model showing standardized path coefficients, standard errors (in parentheses), and amount of variance explained (R^2) for measures of mathematics (a), reading (b), and spelling (c). Bold lines represent paths significant at $p < .05$. AU, Animal Updating; BDR, Backward Digit Recall; LOST, Lost Animals; DCCS, Dimensional Change Card Sort; FL_{I}, Flanker (incongruent condition); FL_{C}, Flanker (congruent condition); HTKS, Heads-Toes-Knees-Shoulders; STA, Statue task; VMS, Visual Motor Skills; DP, Draws a Person; Num, Writes Numerals in Sequence; Letters, Writes Uppercase Letters in Sequence; EF, Executive Function latent factor; FMS, Fine Motor Skills latent factor; Age, age at the first assessment date; TimeK, time spent in kindergarten; Raven, Raven's Coloured Progressive Matrices; SES, Socio-economic status (composite score).

Figure 2. Simple slopes showing significant interactions between executive functions and fine motor skills in mathematics (a) and spelling (b). Significant slopes are marked by an asterisk. FINE, fine motor skills latent factor; EF, executive functions latent factor; LoFMS (-1SD) and HiFMS (+1SD) at fine motor skills mean ±1 *SD*; LoFMS (-2SD) and HiFMS (+2SD) at fine motor skills mean ±2 *SD*; LoEF (-1SD) and HiEF (+1SD) at EF mean ±1 *SD*; LoEF (-2SD) and HiEF (+2SD) at EF mean ±2 *SD*.

Table 1

Fine Motor Skills Assessments

Skill	Sample indicators and maximum score	Assesses
Early fine motor skills [a]	*Easiest skill:* Places fist in mouth *Hardest skill:* Imitates scribble Maximum: 20	Ability to use small muscles of the hands and fingers to grasp and manipulate objects.
Builds tower with blocks [a]	*Easiest skill:* Builds a 2-block tower *Hardest skill:* Builds a 12-block tower Maximum: 11	Ability to stack multiple blocks to build a tower.
Visual motor skills	*Easiest skill:* Scribbles or draws *Hardest skill:* Grasps pencil correctly Maximum: 16	Ability to scribble, draw, and copy forms.
Draws a person	*Body parts:* Head, eyes, legs, mouth, arms, hair, nose, trunk, hands, feet, neck, ears, shoulders Maximum: 13	Ability to draw a person based on child's concept of the body and its individual parts.
Prints personal information [b]	*Easiest skill:* Prints first letter of first name *Hardest skill:* Prints last name Maximum: 3	Early writing skills by evaluating his/her ability to print his/her first and last name.
Writes numerals in sequence	*Numerals:* 1 to 10 Maximum: 10	Early writing skills by evaluating child's ability to write numerals in sequence.
Prints uppercase letters in sequence	*Letters:* A to Z Maximum: 26	Early writing skills and alphabet knowledge.
Quality of printing [b]	Prints manuscript with appropriate slant, size, spacing, shape and formation, alignment, legibility, absence of reversals, and neatness. Maximum: 8	Printing skills.

Note. Maximum score corresponds to number of indicators as each correctly performed indicator is awarded 1 point.

[a] Excluded from formation of latent variable for little to no score variation in current sample.

[b] Not assessed in the present study.

Table 2

Descriptive Statistics and Correlations among Study Variables

	Raven's	SES	Age	TimeinK	Fine	EF	Math	Read	Spell
Raven's		.191**	.267**	.099**	.344**	.503**	.489**	.343**	.358**
SES			.013	.126**	.244**	.284**	.338**	.315**	.306**
Age				.420**	.358**	.318**	.344**	.231**	.269**
TimeinK					.337**	.159**	.242**	.196**	.264**
Fine						.508**	.637**	.531**	.682**
EF							.652**	.437**	.491**
Math								.648**	.665**
Read									.732**
Mean	15.76	0.03	57.33	3.42	0.00	0.00	23.86	15.27	12.57
SD	5.23	0.98	3.88	1.72	0.87	0.85	9.51	5.84	4.08
Min	0	-2.73	49	1	-2.36	-2.04	0	0	0
Max	35	1.76	66	7	1.30	2.56	68	41.5	27

Note. SES = socio-economic status; Age = child's age (in months); TimeinK = Time spent in kindergarten (in months); Fine = Fine motor latent factor scores; EF = executive functioning latent factor scores; *$p < .05$. ** $p < .01$.

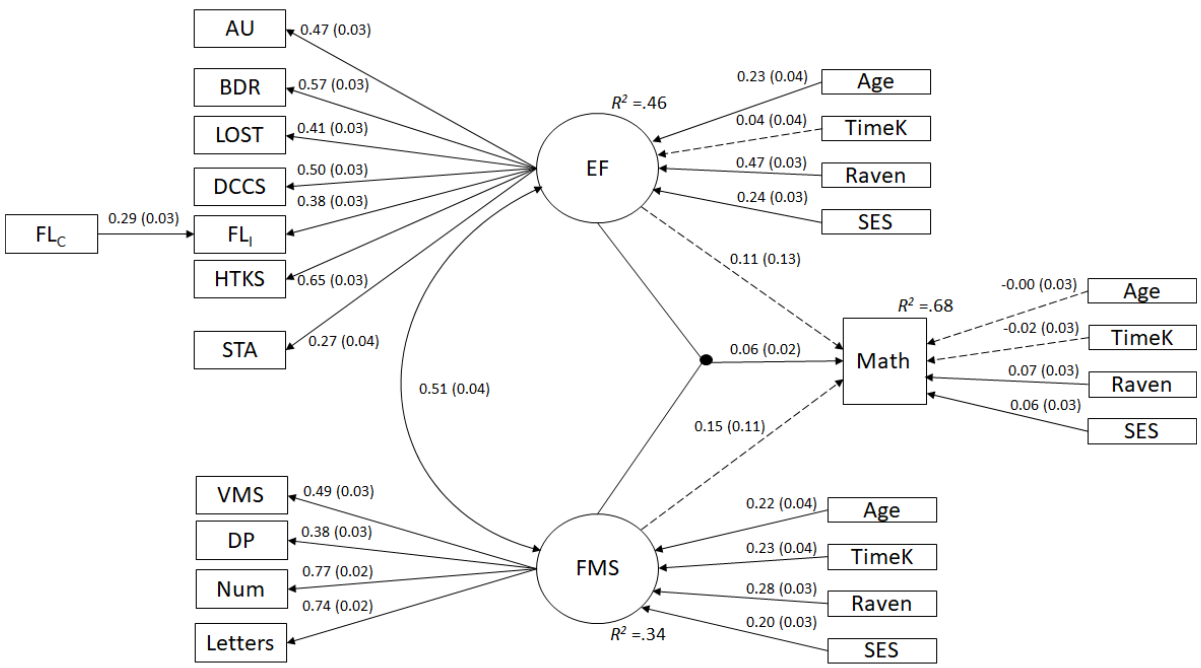

Figure 1(a)

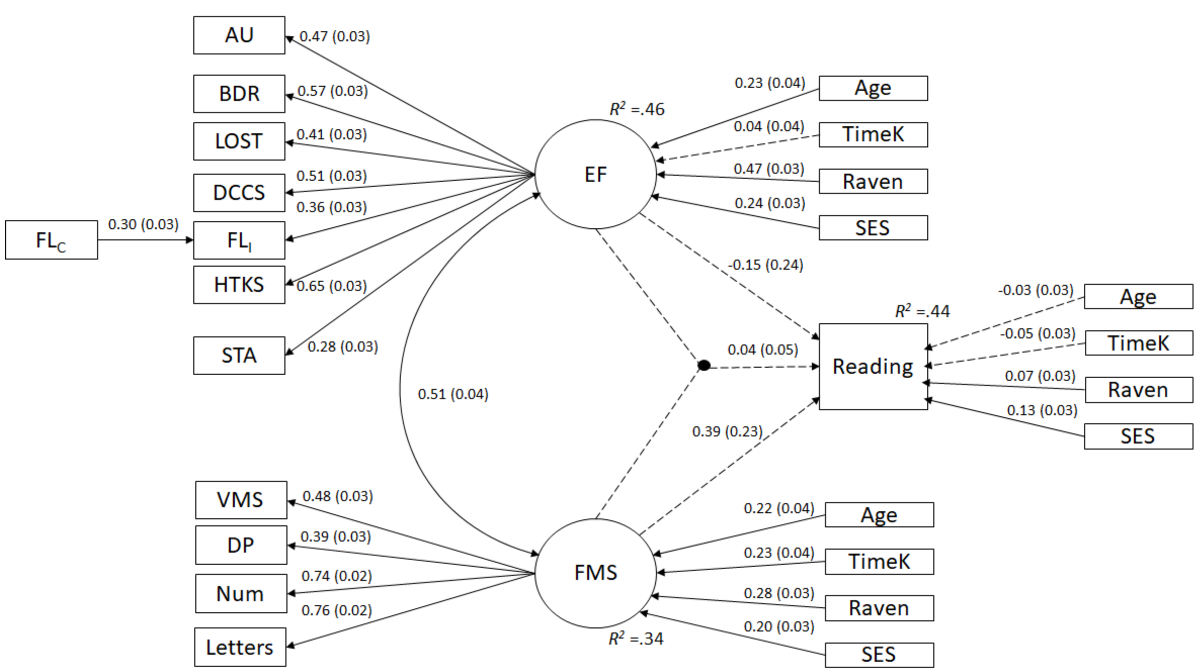

Figure 1(b)

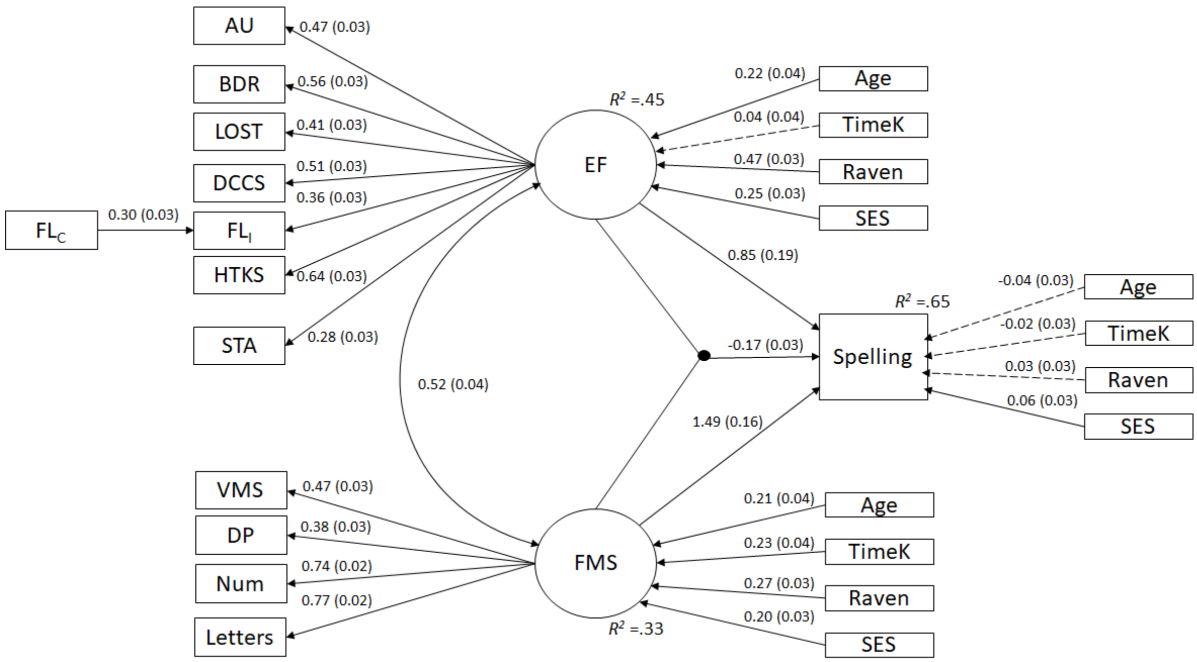
AU
BDR
LOST
DCCS
FLC
FLI
HTKS
STA
0.47 (0.03)
0.56 (0.03)
0.41 (0.03)
0.51 (0.03)
0.36 (0.03)
0.30 (0.03)
0.64 (0.03)
0.28 (0.03)
EF
R2 =.45
Age
TimeK
Raven
SES
0.22 (0.04)
0.04 (0.04)
0.47 (0.03)
0.25 (0.03)
0.85 (0.19)
0.52 (0.04)
-0.17 (0.03)
Spelling
R2 =.65
Age
TimeK
Raven
SES
-0.04 (0.03)
-0.02 (0.03)
0.03 (0.03)
0.06 (0.03)
1.49 (0.16)
VMS
DP
Num
Letters
0.47 (0.03)
0.38 (0.03)
0.74 (0.02)
0.77 (0.02)
FMS
R2 =.33
Age
TimeK
Raven
SES
0.21 (0.04)
0.23 (0.04)
0.27 (0.03)
0.20 (0.03)

Figure 1(c)

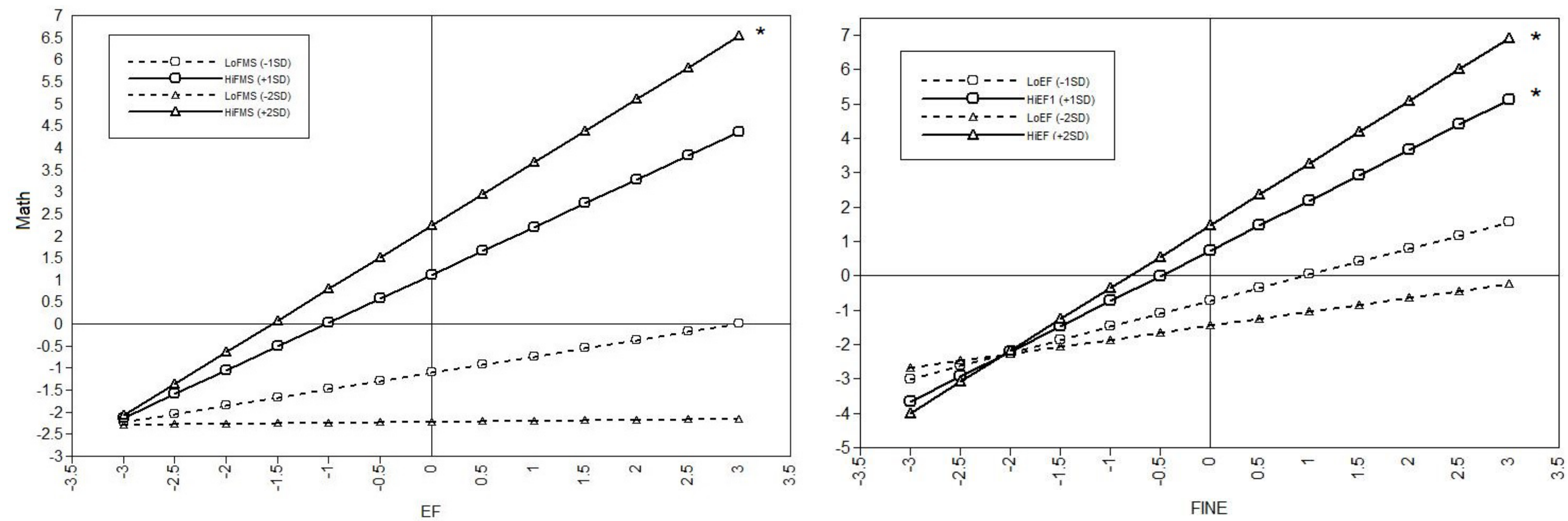

Figure 2(a)

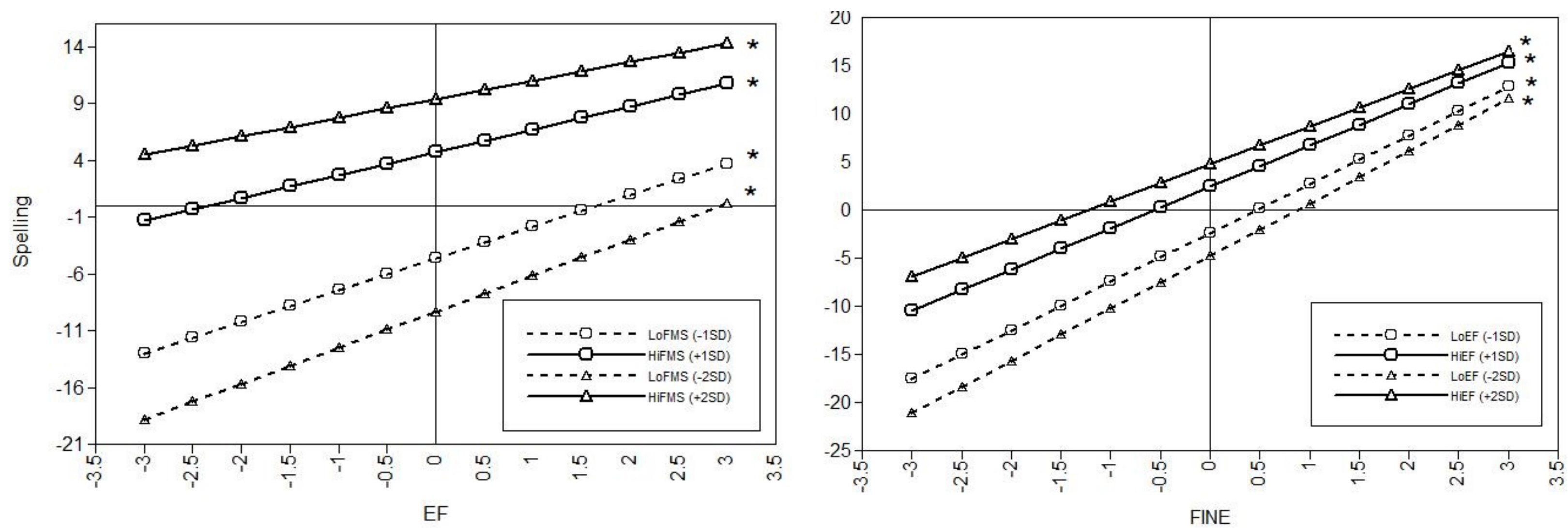

Figure 2(b)