Behavioral Self-Regulation and Executive Function Both Predict Visuomotor Skills and Early Academic Achievement

Derek R. Becker

Oregon State University

beckerde@onid.orst.edu

Alicia Miao

Oregon State University

miaoa@onid.orst.edu

Robert Duncan

Oregon State University

duncarob@onid.orst.edu

Megan McClelland

Oregon State University

megan.mcclelland@oregonstate.edu

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Abstract

The present study explored direct and interactive effects between behavioral self-regulation (SR) and two measures of executive function (EF, inhibitory control and working memory), with a fine motor measure tapping visuomotor skills (VMS) in a sample of 127 prekindergarten and kindergarten children. It also examined the relative contribution of behavioral SR, EF, and VMS skills for concurrent academic achievement. Results indicated that a measure of working memory (WJ-Working Memory) and a measure of behavioral SR (Head-Toes-Knees-Shoulders task; HTKS) were directly related to VMS. Differential relations were also examined for prekindergarten and kindergarten children. Results revealed a significant interaction between age and inhibitory control (Day-Night), and an interaction at a trend level between age and working memory suggesting both tasks are more related to VMS skills for younger children. Results also indicated that behavioral SR, EF, and VMS skills were differentially related to the three achievement outcomes. Both behavioral SR and VMS were significantly related to math, behavioral SR, EF, and VMS were significantly related to emergent literacy, and behavioral SR and EF were related to vocabulary scores. Results point to significant relations between behavioral SR and EF with VMS, and how each is related to early academic achievement in preschool and kindergarten.

Behavioral Self-Regulation and Executive Function Both Predict Visuomotor Skills and Early Academic Achievement

As researchers examine the cognitive and behavioral skills involved in early academic achievement, new research suggests that components of fine motor skills play an important role in facilitating the learning process. Fine motor skills can be delineated into tasks involving motor control (e.g., tracing), or tasks that integrate motor and spatial abilities (visuomotor skills, e.g., copying a geometric shape) (Carlson, Rowe, & Curby, 2013). Visuomotor skills (VMS) are related to both math and emergent literacy (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010), and are emerging as discrete skills involved in early learning (Cameron et al., 2012). Although VMS are a unique predictor of early achievement, it is not fully understood why these skills are linked to academic success, or if components of cognition enhance or predict VMS. Executive function (EF) is a set of cognitive processes involved in higher-level, goal-directed processing consistently linked to early achievement (Blair & Razza, 2007), which manifests as behavioral self-regulation (SR) (McClelland et al., 2007), and both could play a role in VMS. Indeed, the link between SR and EF with VMS is supported by behavioral (Decker, Englund, Carboni, & Brooks, 2011), biological (Diamond, 2000), and cognitive research (Boncoddo, Dixon, & Kelley, 2010). Yet studies looking at direct connections between behavioral SR and EF with VMS have not consistently demonstrated strong connections (Cameron et al., 2012; Grissmer et al., 2010).

Additionally, little research has explored relations between the different dimensions that form the EF construct (i.e., working memory, cognitive flexibility, inhibitory control; Garon, Bryson, & Smith, 2008) with VMS, or explored the relative contribution of the different dimensions of EF relative to VMS concurrently with academic achievement. Given that VMS are a strong predictor of early academic outcomes (Cameron et al., 2012; Grissmer et al., 2010; Son

& Meisels, 2006), it is also possible that different dimensions of EF (e.g., working memory) could differentially relate to achievement when assessed relative to VMS. For example, tasks that integrate motor and visual processes are highly related to the development of literacy and math skills (Puranik & Lonigan, 2012; Zebian, 2005), with the connection between literacy, numeracy, and VMS possibly augmented through writing numbers and letters. As such, it is possible when VMS are assessed with working memory, they might be more strongly related to emergent literacy and math. In the present paper, utilizing a concurrent research design, we explored direct connections between behavioral SR and EF with VMS, and assessed if behavioral SR and EF are differentially related to VMS for prekindergarten- and kindergarten-age children. We also examined if behavioral SR, EF, and VMS differentially relate to academic achievement in prekindergarten and kindergarten children.

Visuomotor Skills and Academic Achievement

It is estimated that preschoolers and kindergarteners spend between 27% and 66% of the school day working on some form of fine motor activity (Marr, Cermak, Cohn, & Henderson, 2003), which makes fine motor skills an important aspect of early school readiness (Bredekamp & Copple, 1997; Johnson, Gallagher, Cook, & Wong, 1995; Lillard, 2005). Fine motor measures usually examine some level of visual motor integration, spatial organization, manual control, or perceptual ability, and often ask the child to trace, manipulate blocks, or copy and create an external image. In the present study, we measured children's ability to copy a series of geometrics shapes, and define fine motor skills as visuomotor skills (VMS), which incorporates visual spatial processing, movement within small muscle systems, and hand-eye coordination.

The idea of *learning to learn* (Adolph, 2005), suggests early learning is centered around the motor system, with brain systems involved in posture, gripping, vision, and motor control acting in concert. As the child adapts to changing environmental demands, both cognitive and motor skills develop together. The coordination of reaching, grasping, and walking must take place to produce solutions to novel locomotor challenges (Adolph, 2008), with this motor flexibility acting as the earliest form of learning and setting the stage for higher level processing (Bushnell & Boudreau, 1993). Anatomical connections between brain systems involved in balance and EF (Diamond, 2000) support the early link between gross motor movement and learning. Further, the theory of embodied cognition links the body and motor system to language comprehension (Fischer & Zwaan, 2008), memory (Barsalou, 1999), problem solving (Boncoddo et al., 2010), and spatial processing (Moreau, 2013a).

Consistent with the above framework, evidence shows spatial processing and EF can be hindered by physically restraining the arm and hand (Moreau, 2013a, 2013b). This is not to say the physical body is the only system involved in spatial processing and EF, but that fine motor movements could play a role in this process. Further evidence for a link between the body and visuomotor skills with academic achievement is found in work linking visual-spatial working memory to math and literacy (St Clair-Thompson & Gathercole, 2006), and overlapping brain networks to both visuospatial and numerical processing (Hubbard, Piazza, Pinel, & Dehaene, 2005). Visuospatial processes are also spontaneously engaged when individuals are actively processing arithmetic and numerical information (e.g., Dehaene, 1992).

Aside from spatial processing, at the classroom level, children with better VMS are more likely to show a faster rate of automaticity, allowing for an easier translation of letters and numbers to paper. As skills become automatized, activity moves from cortical to sub-cortical regions, which frees up cognitive resources (Floyer-Lea & Matthews, 2004). For children with better VMS, less conscious attention would be focused on scripting letters and numbers, allowing for cognitive energy to be distributed to connecting figures and sounds, decoding words, and understanding mathematical concepts. Consequently, problems integrating visual perception, posture, motor control, and VMS are often reflected in academic difficulties (Alloway & Archibald, 2008; American Psychiatric Association, 2010).

Measures of visual-motor coordination (e.g., tracing tasks), VMS, and gross motor skills have been assessed in relation to achievement (Carlson et al., 2013; McPhillips & Jordan-Black, 2007), with a preponderance of work showing VMS tasks, compared with tracing and gross motor measures, are a better gauge of academic outcomes (Bart, Hajami, & Bar-Haim, 2007; Cameron et al., 2012; Carlson et al., 2013). This is demonstrated by studies examining longitudinal connections between VMS and achievement, which show that VMS in kindergarten predict third grade literacy (Taylor, 1999), math, and spelling scores (McPhillips & Jordan-Black, 2007). Aggregating three longitudinal data sets, Grissmer and colleagues (2010) showed that VMS at kindergarten entrance predicted third and fifth grade literacy and math achievement.

In a recent study by Cameron and colleagues (2012), VMS measured prior to entering kindergarten significantly predicted fall letter-word identification, reading comprehension, and sound awareness, as well as improvement in these scores from fall to spring. Finally, in a cross-sectional sample between the ages of five and eighteen, strong VMS related to higher math and writing scores after controlling for visual-motor coordination (i.e., tracing) (Carlson et al., 2013). The significant connections between VMS and achievement highlight the need to understand what other skills relate to VMS.

Behavioral Self-Regulation, Executive Function, and Achievement

Executive function (EF) is a set of cognitive processes involved in higher-level, goal-directed processing that has been consistently linked to academic success (Duncan et al., 2007;

McClelland & Cameron, 2011). Although the processes that comprise the EF construct are highly interrelated, they are often delineated into distinct components (Hughes, 1998; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). This framework, known as the *unity and diversity construct of EF* (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), incorporates updating (i.e., working memory), cognitive flexibility, and inhibitory control (Best & Miller, 2010). As EF is involved in the regulation of both thought and action (Koziol et al., 2012), the construct of behavioral self-regulation (SR) is viewed as the behavioral manifestation of EF (Barkley, 1997; 2011; McClelland & Cameron, 2012). In general, EF is required to modify overt behavior and this can be assessed through measures of behavioral SR.

Within the classroom, a child must seamlessly integrate behavioral SR and EF as they shift between tasks, interact with peers, and follow directions. For example, as a child moves from free play to teacher-led instruction, they must inhibit the prepotent tendency to continue playing, move to the new activity, listen for directions, and hold in mind and follow the teacher's instructions. The prefrontal cortex is a critical system for carrying out these actions (Arnsten & Li, 2005; Duncan & Owen, 2000), and shows heightened development between ages two and five (Posner, Rothbart, Sheese, & Voelker, 2012; Rothbart, Ellis, Rueda, & Posner, 2003). This makes the prekindergarten and kindergarten years a salient time for examining behavioral SR and EF.

Studies looking at connections between behavioral SR and EF with achievement in prekindergarten populations consistently show both are related to higher academic outcomes. For example, inhibition is a key factor involved in academic learning (Borella, Carretti, & Pelegrina, 2010; Bull & Scerif, 2001; D'Amico & Passolunghi, 2009). In one study, Bull & Scerif (2001) examined different components of EF as a predictor of mathematics ability, and found that poor inhibitory control was the key component related to lower math scores at age 7. Other work finds similar effects with measures of attention, which predicts early (Duncan et al., 2007) and long-term academic success (McClelland, Acock, Piccinin, Rhea, & Stallings, 2013).

At the same time, a child's ability to shift focus between tasks and inhibit inappropriate actions is a key component of early learning. This was demonstrated by Blair & Razza (2007), who found children with better inhibition who could shift attention (cognitive flexibility) had significantly higher math and literacy scores. Finally, both working memory and behavioral SR measured at the start of prekindergarten significantly predict literacy and math skills at the end of the academic year (McClelland et al., 2007; Welsh, Nix, Blair, Bierman, & Nelson, 2010). These studies highlight the strong interconnection between behavioral SR, EF, and academic achievement, suggesting children who can inhibit inappropriate actions, focus attention, remember, hold, and manipulate information, and appropriately shift between tasks also have higher math and literacy scores.

Connections Between Visuomotor Skills, Behavioral Self-Regulation, and Executive Function

In general, tasks that require a child to copy an external image integrate motor control with behavioral SR and EF, as they require spatial organization, the ability to visualize an image, hold the image in short-term memory, and transfer the image with the correct proportions onto paper. The few studies examining connections between VMS and EF have mainly focused on clinical samples (i.e., Attention Deficit Hyperactivity Disorder, preterm infants) and show a relationship between both VMS and EF within these populations (Baron et al., 2009; Böhm, Lundequist, & Smedler, 2010; Mariani & Barkley, 1997). Other work examining typically developing children finds higher-level processing involving EF, along with working memory, positively relates to VMS in children between four and six years of age (Decker et al., 2011).

Further evidence for a link between VMS, behavioral SR, and EF suggests they are connected by overlapping neural networks. For example, brain areas involved in motor activity, such as the cerebellum and basal ganglia, are also associated with cortical systems involved in executive control (Davis, Pitchford, Jaspan, McArthur, & Walker, 2010; Diamond, 2000). In research looking at both cortical and subcortical activity in children between the ages of 6 and 13, cerebellar volume was positively correlated with cognitive ability (Pangelinan et al., 2011). Other work (Marvel & Desmond, 2010b) shows that as EF demands are amplified, activity in both the cerebellum and cortex increase.

Within the learning context, better VMS could relate to faster automaticity, which is directly related to cerebellar function (Floyer-Lea & Matthews, 2004). For example, increased cerebellar and prefrontal activity is found during novel cognitive and motor tasks, with automaticity reducing activity in the prefrontal cortex (Hua & Houk, 1997). This automaticity could allow children to divide their attentional capacities between tasks, aiding in the learning of new materials in school. The above studies offer both behavioral and biological support linking behavioral SR and EF to VMS, suggesting overlapping neural systems could relate to deficits in both (Diamond, 2000; Wilson et al., 2013).

Work examining connections between behavioral SR, EF, and VMS with achievement, however, has not consistently demonstrated strong connections. For example, Cameron et al. (2012), using a composite measure of VMS, showed behavioral SR and VMS were moderately correlated ($r = .32$) and acted as unique predictors of academic achievement in prekindergarten children. In a separate study that also measured VMS and EF in kindergarten, Grissmer et al. (2010) did not examine direct relations between EF and VMS, but found that both attention and

VMS were significantly related to academic outcomes. Given the above support suggesting behavioral SR, EF, and VMS could have overlapping neural underpinnings (e.g., Diamond, 2000; Pangelinan et al., 2011), the present study built on past work by assessing connections with VMS using multiple measures that included a behavioral measure of SR and two cognitive measures of EF (working memory, inhibitory control).

Age-Related Variability in the Development of Behavioral Self-Regulation, Executive Function, and Visuomotor Skills

Evidence supporting connections between behavioral SR and EF with VMS (Decker et al., 2011), coupled with limited research within non-clinical populations, point to a need to look deeper within the components of EF and assess variability in these skills in prekindergarten and kindergarten. Core components of EF develop during the prekindergarten and kindergarten years (Carlson, 2005; Rothbart & Posner, 2001), with rapid changes found between age three and seven in working memory (Diamond, Prevor, Callender, & Druin, 1997; Ewing-Cobbs, Prasad, Landry, Kramer, & DeLeon, 2004; Gathercole, 1998; Luciana, & Nelson, 2002), inhibitory control (Diamond et al., 1997; Gerstadt, Hong, & Diamond, 1994), and cognitive flexibility (Schutte, Spencer, & Schöner, 2003).

Similar to EF, age is also a significant factor accounting for variability in VMS (Decker et al., 2011; Koppitz, 1975). For example, with a sample of children between four and seven, age significantly related to VMS on the Bender Visual-Motor Gestalt Test, with performance improving with age (Decker et al., 2011). With a similar age sample, Rhemtulla and Tucker-Drob (2011) showed that VMS improved between prekindergarten and kindergarten and followed a similar trajectory with literacy and math. Evidence also indicates that EF is experience dependent, with continued exposure to incrementally harder tasks improving EF in children between age three and five (Dowsett & Livesey, 2000). Other work shows improvement in behavioral SR and EF is related both to maturation and exposure to demanding EF and SR tasks between age four and six (Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005; Tominey & McClelland, 2011). Thus, as children are exposed to more visuomotor activities and develop better behavioral SR and EF the connection with VMS could start to attenuate.

At the same time, better VMS could aid behavioral SR and EF by freeing cognitive resources, allowing the child to divide attention between tasks that require visual and motor skills. Although there is evidence for reciprocal directionality between EF and VMS (Cisek & Kalaska, 2010; Wilson et al., 2013), the majority of work suggests EF is playing a role in VMS (Böhm et al., 2010; Decker et al., 2011; Koziol, Budding, & Chidekel, 2012; Marvel & Desmond, 2010b). Thus, the present study examined if behavioral SR and EF were concurrently related to VMS and if age moderates these relationships.

Connections Between Behavioral Self-Regulation, Executive Function, Visuomotor Skills, and Academic Achievement

Although behavioral SR, EF, and VMS are separately related to academic outcomes, the few studies that have included components of the three with academic achievement show each relate to literacy and math (Cameron et al., 2012; Grissmer et al., 2010). These studies are useful in furthering our understanding of the unique predictability of behavioral SR, EF, and VMS on children’s achievement, but are also limited because they used observer-rated EF (Grissmer et al. 2010), or used a single direct assessment of behavioral SR (Cameron et al., 2012). Assessing VMS with multiple direct assessments of EF (i.e., working memory, inhibitory control) and behavioral SR may offer a better understanding of the role each play with math and emergent literacy skills.

For example, working memory and VMS could be more related to emergent literacy compared to inhibitory control, as both might be more involved in learning letter names and sounds through the act of copying (Puranik & Lonigan, 2012). It is also possible behavioral SR and VMS will be more strongly associated with math relative to inhibitory control and working memory, as past work shows both relate to math (Cameron et al., 2012; Carlson et al., 2013; McClelland et al., 2007). Finally, given that both math and emergent literacy often involve copying numbers and letters, VMS are likely more related to achievement outcomes that involve direct physical learning (i.e., writing letters and numbers) rather than learning involving vocabulary knowledge (Cameron et al., 2012; Decker et al., 2011).

Summary and Hypotheses

In the present study, we had three research questions. First, using a measure of behavioral SR and two EF tasks, we assessed direct relations between components of EF and behavioral SR with VMS. Working from both behavioral (Decker et al., 2011; Pellicano, Maybery, & Durkin, 2005) and brain research (Davis et al., 2010; Diamond, 2000), we hypothesized that the three tasks would be positively and significantly concurrently related to VMS with a sample of prekindergarten and kindergarten children. We included maternal education, English language learner (ELL) status, child gender, and child age as covariates, as these factors are shown to significantly relate to early academic outcomes, behavioral SR, and EF (Evans & Rosenbaum, 2008; Matthews, Cameron Ponitz, & Morrison, 2009; McClelland et al., 2007; Wanless, McClelland, Tominey, & Acock, 2011).

Second, we examined if the relationship between behavioral SR and EF with VMS varied as a function of age. Given that there is significant growth occurring in EF between the ages of three and seven (Carlson, 2005; Rothbart & Posner, 2001), coupled with evidence that behavioral

SR and EF are experience dependent (Dowsett & Livesey, 2000; Tominey & McClelland, 2011), we hypothesized that age will moderate the relationship between aspects of EF (e.g., inhibitory control) and behavioral SR with VMS, with the link being stronger for younger children relative to older children.

Finally, we assessed if VMS, behavioral SR, and EF were significantly related to academic achievement. Based on previous research (Bull, Espy, & Wiebe, 2008; Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010), we expected that VMS and working memory would be more strongly related to emergent literacy, and behavioral SR and VMS would be strongly related to math. For example, measures of working memory in preschool are found to relate to early literacy skills (Alloway et al., 2005; Bull et al., 2008), with behavioral SR consistently related to higher math scores (Becker, McClelland, Loprinzi, & Trost, 2014; Cameron et al., 2012). Further, the writing of letters and numbers is related to both numeracy and literacy development (Dehaene, 1992; Puranik & Lonigan, 2012; Puranik, Lonigan, & Kim, 2011; Zebian, 2005), with children with better VMS showing higher math and literacy scores (Cameron et al., 2012; Grissmer et al., 2010; McPhillips & Jordan-Black, 2007; Taylor, 1999). Finally, we hypothesized that VMS and the behavioral SR and EF tasks would significantly relate to vocabulary, with VMS showing the weakest effect (Cameron et al., 2012).

Method

Participants

Participants were recruited from a small city in the Pacific Northwest and represented a diverse sample of children from middle- and low-income households. The sample consisted of 127 children (49 from prekindergarten and 78 from kindergarten) with a mean age of 68.55 months and a range of 53 to 80 months (*SD* = 7.75). The sample was roughly 67% White, 2%

African American, 15% Latino or Hispanic, 5% Asian or Pacific Islander, and 11% another ethnicity. The kindergarten sample was significantly older than the prekindergarten sample (74 months for kindergarten versus 59.88 months for prekindergarten). The average years of maternal education was 15.67 years (*SD* = 3.23), however the prekindergarten sample had significantly lower maternal education (14.21 years for prekindergarten versus 16.57 years for kindergarten). Furthermore, 53% of the prekindergarten sample was enrolled in Head Start. The percentage of kindergarten children that were in Head Start prior to kindergarten entry is unknown, although the vast majority (34 of 35, or 97%) of parents that responded reported their child attended at least one month of preschool.

There were five Spanish-speaking children in the prekindergarten sample (all Head Start) and three Spanish-speaking children in the kindergarten sample. The Spanish-speaking children did not statistically or substantively differ from their peers on maternal education, child gender, child age, or any academic achievement outcome. Children and families were recruited with letters sent home with an explanation of the study and consent information, with all children part of a larger study on school readiness. Other work from the larger study has examined relations between a teacher-reported, a directly assessed, and an observational measure of self-regulation and early math and literacy using a different cohort of children (Schmitt, Pratt, & McClelland, 2014). Data collection for both prekindergarten and kindergarten children was conducted during the spring of the school year.

Procedure

After receiving consent, children were tested two to three times during brief sessions (10-20 minutes each) in a quiet location at their school. Assessment administration was randomized in order to control for order effects. Trained research assistants administered each session.

Spanish-speaking children were identified by their teachers and received all of the measures in a Spanish version from fluent Spanish-speaking research assistants.

Direct Assessments of Behavioral Self-Regulation and Executive Function

Behavioral self-regulation. The extended version of the Head-Toes-Knees-Shoulders (HTKS) task is a measure of behavioral self-regulation that requires cognitive flexibility, working memory, and inhibitory control (Cameron Ponitz, McClelland, Matthews, & Morrison, 2009; McClelland & Cameron, 2012). The task requires different components of executive function, such as inhibitory control, by having the child attend to rules in which a natural response must be inhibited and the opposite of a command performed. In addition, working memory and attentional shifting are required by the assessment, and previous research has found that the task is related to all aspects of EF (Lan, Legare, Cameron Ponitz, Li, & Morrison, 2011; Mähler, Schuchardt, Piekny, von Goldammer, & Grube, 2012; McClelland et al., 2014). Children are given up to four commands (e.g., “touch your head,” “touch your toes,” “touch your knees” and “touch your shoulders”), and then told they are going to play a game and do the opposite of each command. The last part of the task switches the rules so children must retain the new rule and do the opposite of the verbal command. Each incorrect response is coded as 0, a self-corrected response is coded as 1 point, and a correct response is coded as 2 points. There are a total of 30 items with a possible scoring range of 0 – 60. The HTKS has been shown to have high inter-rater reliability (Cameron Ponitz et al., 2008), to be reliable and valid in different cultures, and to be significantly predictive of academic achievement (Cameron Ponitz et al., 2009; McClelland et al., 2007; von Suchodoletz et al., 2013; Wanless, McClelland, Acock, Cameron Ponitz, et al., 2011; Wanless, McClelland, Acock, Chen, & Chen, 2011). Of the 121 children that received the HTKS in the current study, 26 randomly selected children (*n* = 14 prekindergarten, *n* = 12 kindergarten) were videotaped and recoded to assess inter-rater agreement. The inter-rater agreement for this subsample was 92.79% with a weighted Cohen's kappa of .80 and correlated at $r = .86$, $p < .001$.

Inhibitory control. The Day-Night Stroop task (Gerstadt et al., 1994) is a measure of inhibitory control in which the child must inhibit a predominant response by verbally responding to a picture of a sun as "night" and a picture of a moon as "day." The task is measured with 16 trials where the child must say the opposite of what the picture is depicting. No responses and incorrect responses are coded as 0, self-corrected responses are coded as 1, and correct responses are coded as 2, with the range of scores from 0 – 32. The Day-Night has been shown to be a reliable and valid assessment in prekindergarten- and kindergarten-age children (Carlson, 2005; Gerstadt et al., 1994). The current study sample had a Cronbach's $\alpha = .92$.

Working memory. The Woodcock-Johnson Auditory Working Memory subtest (Woodcock, McGrew, & Mather, 2001) is a working memory task that requires the child to repeat back to the assessor a list of numbers and objects. The task begins with one number and one object, and then increases in difficulty with additional numbers and objects. The numbers and objects are presented in differing orders, but the child must always repeat back the objects first then the numbers in the correct order. If only the objects or the numbers are repeated back correctly in the correct order (objects first, then numbers), partial credit is given. W-scores, which were developed with Rasch-based measurement models to create equal-interval scale characteristics (Mather & Woodcock, 2001a), were used in the current analyses. The W-scores are centered at 500, which is the approximate average performance of a 10-year-old child and were significantly correlated to the standardized score ($r = .96$) and the percentile rank ($r = .96$) in our sample. Although internal reliability data was not available in the present sample, the

Auditory Working Memory subtest is widely used, normed, and standardized, and has very strong median split-half reliability of .93 for children four to seven years old (Mather & Woodcock, 2001a).

Visuomotor Skills

Beery Visual-Motor Integration (VMI). The Beery Visual-Motor Integration 6th Edition (VMI; Beery & Beery, 2010) requires the child to demonstrate fine motor skills by accurately copying figures. The assessment begins with copying a vertical line, a horizontal line, and a circle. As the task progresses, figures get increasingly more difficult to copy (e.g., square, triangle, and combinations of circles). In total, 21 figures were copied and raw scores were calculated based on the number of correctly recreated figures (1 point), for a possible range between 0 – 21. The VMI is valid and reliable, with a reliability coefficient alpha between .80 - .86 for children 4- to 7-years old and an inter-rater median reliability coefficient of .93 (Beery & Beery, 2010). Of the 118 children that completed the VMI, 20 assessments were randomly selected to be double-coded in order to check inter-rater agreement. The inter-rater agreement for the raw score on the VMI for this subsample was 93.00% with a weighted Cohen’s kappa of .78 and correlated at $r = .95$, $p < .001$.

Achievement Outcomes

All achievement outcomes utilized W-scores from subtests from the Woodcock-Johnson Psycho-Educational Battery – III Tests of Achievement (WJ – III; Woodcock et al., 2001) or the Batería Woodcock-Muñoz (Muñoz-Sandoval, Woodcock, McGrew & Mather, 2005). As with the Auditory Working Memory subtest, W-scores were used because they utilize Rasch-based measurement models to create equal-interval scale characteristics (Mather & Woodcock, 2001b). The WJ – III is widely used and standardized with strong reliability and validity in both English-and Spanish-speaking children (Mather & Woodcock, 2001b; McGrew & Woodcock, 2001; McGrew, Schrank, & Woodcock, 2007; Woodcock & Mather, 2000). The English and Spanish WJ – III measures have been equated using item response theory methodology and indicate that they assess the same competencies (Woodcock & Muñoz-Sandoval, 1993, 1996), with recent research showing no significant differences on scores between the two versions (Hindeman, Skibbe, Miller, & Zimmerman, 2010).

Math. The Applied Problems subtest involves understanding quantities, simple calculations, and solving practical problems using mathematical skills. In our sample, the Applied Problems W-score was highly correlated with the standardized score (r = .80) and with percentile rank (r = .78). For children ages two to seven, the subtest has a test-retest reliability of .90 for a less than 1-year interval and .85 for a 1- to 2-year interval, and a median split-half reliability of .92 for children four to seven years old (McGrew & Woodcock, 2001).

Emergent literacy. The Letter-Word Identification subtest requires the child to identify letters and pronounce words (both receptive and expressive). In our sample, the Letter-Word Identification W-score was highly correlated with the standardized score (r = .87) and with percentile rank (r = .79). For children ages two to seven, the subtest has a test-retest reliability of .96 for a less than 1-year interval and .91 for a 1- to 2-year interval, and a median split-half reliability of .98 for children four to seven years old (McGrew & Woodcock, 2001).

Picture vocabulary. The picture-vocabulary subtest requires the child to point to or name a target picture and includes both receptive and expressive vocabulary. The Picture Vocabulary W-score was highly correlated with the standardized score (r = .93) and with percentile rank (r = .90) in our sample. The subtest has a median split-half reliability of .73 for children four to seven years old (McGrew & Woodcock, 2001).

Analytic Plan

Stata 12.1 (StataCorp., 2011) was used to obtain descriptive statistics, analyze missing data, and perform data analyses. Initial multivariate regression analyses were performed, and final models were estimated using the SEM command in Stata to adjust standard errors for clustering of children within classrooms using full information maximum likelihood to address the issue of missing data (Schafer & Graham, 2002). Results obtained with the final Stata SEM models are presented here. A number of variables used in the current analyses had missing data. The *N*'s for the variables in the model can be seen in Table 1. Measures for maternal education, VMS, working memory, and mathematics contained between 7.1% and 21.2% missingness. Data were assumed to be missing at random (MAR). To examine the MAR assumption for these data, missing data indicator variables were created and used as dependent variables in logistic regressions. Independent variables used to predict missingness included all variables from the current analyses, as well as additional variables available in the dataset that could be theoretically related to missingness and that contained less than 5% missing data. No variables examined were found to predict missingness in logistic regression analyses, indicating that the MAR assumption was reasonable, although there is no way to definitively test this. Children were nested within 17 classrooms (range: 2 – 21 children in each classroom) in 8 schools (range: 4 – 49 children in each school). Intra-class correlation coefficients (ICCs) at the school level were very small (ICC range: <.001 - .03). At the classroom level, ICCs ranged from .14 to .37. Standard errors were adjusted in Stata to account for clustering at the classroom level. However, due to the small number of classrooms in the current study, and the number of classrooms containing few individuals (29% of classrooms contained 4 or fewer children), multilevel modeling was not used.

To address the first research question, a model was estimated with the three behavioral SR and EF tasks predicting VMS. To address the second research question, interactions between the three behavioral SR and EF tasks and age were added one at a time to examine their unique effects in predicting VMS. All variables were centered prior to construction of interaction terms, following the recommendation by Aiken and West (1991). Finally, to address the third research question, three models were estimated to predict the three achievement outcomes from the three behavioral SR and EF tasks and the VMS task. The final models are described in the Appendix.

Data were examined for univariate normality and outliers. Although the distribution of the Day-Night inhibitory control task was somewhat skewed, values of skewness and kurtosis did not exceed the acceptable ranges for normal distributions (Kline, 2005). Outliers were classified as values which were greater or lesser than 3.3 standard deviations from the mean. One outlier was found for each of the following measures: Day-Night, VMS, Applied Problems, and Picture Vocabulary. Each outlier was recoded to the next closest valid value for that measure within +/- 3.3 standard deviations. Standardized estimated parameter coefficients were similar in analyses where outliers were and were not recoded. Results for analyses that included the recoded outlier cases are presented in the current study.

Results

Descriptive statistics for all variables included in the current analyses are presented in Table 1 and are shown for the overall sample, and separately for prekindergarten and kindergarten children. Although statistics for skewness were not outside of the acceptable range for the sample, the overall mean for inhibitory control as measured by the Day-Night inhibitory control task was somewhat high. Possible scores for inhibitory control ranged from 0 – 32. Prekindergarten children (average age = 59.88 months) had mean inhibitory control scores of

23.75, and kindergarten children (average age = 74 months) had a higher overall mean inhibitory control score of 29.21. Unadjusted bivariate correlations showed significant associations between the academic outcomes, VMS, the behavioral SR and EF tasks, and the maternal education and child age covariates (see Table 2). T-tests showed no significant gender differences for any of the variables in the current analyses. Behavioral SR and working memory were highly correlated ($r = .61$, $p < .001$), although significant relations were found among all behavioral SR and EF tasks *(rs* ranging from .31 to .61, *ps* $< .001$). Of the three behavioral SR and EF tasks, behavioral SR showed the strongest association to VMS ($r = .60$, $p < .001$) and the three academic outcomes *(rs* ranging from .60 to .74, *ps* $< .001$).

Research Question 1: Are The Three Behavioral SR and EF Tasks Associated with VMS?

Results indicated that behavioral SR and working memory were concurrently associated with VMS for the combined sample of prekindergarten and kindergarten children in the spring. Parameter estimates are presented in Table 3. Behavioral SR ($\beta = .28$, B = .05, $p = .035$) and working memory ($\beta = .14$, B = .02, $p = .026$) were significantly associated with VMS, adjusting for ELL status, child gender, child age, and maternal education. Specifically, higher behavioral SR and working memory scores were related to significantly stronger VMS in prekindergarten and kindergarten children. Additionally, inhibitory control on the Day-Night task was marginally associated with VMS ($\beta = .15$, B = .07, $p = .083$). ELL status, child gender, child age, and maternal education explained 39.14% of the variance in VMS, and the three behavioral SR and EF tasks explained an additional 10.36% of the variance in children’s VMS.

Research Question 2: Do the Relationships Between the Behavioral SR and EF Tasks with VMS Vary as a Function of Child Age?

Our second research question examined interactions between each of the behavioral SR and EF tasks, VMS, and child age (see Table 4). Results indicated significant variation by child age for inhibitory control in concurrently predicting VMS in the spring. The interaction for child age with inhibitory control was significantly associated with VMS ($\beta = -.24$, $B = -.01$, $p = .003$). Specifically, higher inhibitory control scores were positively related to higher VMS scores in younger children, whereas older children with higher inhibitory control scores did not perform significantly better on the VMS task compared to older children with lower inhibitory control scores (see Figure 1). The interaction between child age and inhibitory control explained an additional 2.94% of the variance in VMS scores, after accounting for covariates, behavioral SR, and the two EF tasks.

In addition, the interaction for child age with working memory was marginally associated with VMS performance ($\beta = -.11$, $B = -.00$, $p = .063$). Younger children with higher working memory scores trended toward performing better on the VMS task than younger children with lower working memory scores (see Figure 2). The interaction between child age and working memory explained an additional 1.52% of the variance in VMS scores, after accounting for covariates and the three EF tasks. The interaction for child age with behavioral SR was not significantly associated with VMS scores ($\beta = -.06$, $B = -.00$, $p = .564$), suggesting behavioral SR was similarly associated with VMS performance for younger and older children.

Research Question 3: How Are the Behavioral SR and EF Tasks and VMS Associated with Academic Outcomes?

Results indicated that behavioral SR, the EF tasks, and VMS were significantly associated with emergent literacy, with behavioral SR significantly associated with math and vocabulary for the overall sample of children in the spring (see Table 5). Specifically, children’s

VMS ($\beta = .18$, *B* = 2.65, *p* = .05), inhibitory control ($\beta = .13$, *B* = .83, *p* = .01), behavioral SR ($\beta = .16$, *B* = .39, *p* = .05), and working memory ($\beta = .22$, *B* = .50, *p* = .001) scores were positively associated with children's emergent literacy scores, adjusting for ELL status, child gender, child age, and maternal education. Higher VMS, working memory, inhibitory control, and behavioral SR scores were related to higher emergent literacy scores.

For math, children's performance on the VMS task ($\beta = .13$, *B* = .88, *p* = .05) and behavioral SR ($\beta = .42$, *B* = .49, *p* = .001) were significantly related to math, adjusting for ELL status, child gender, child age, and maternal education. Additionally, inhibitory control was marginally related to math ($\beta = .13$, *B* = .41, *p* = .060). Working memory was not significantly associated with children's math performance.

For children's vocabulary, inhibitory control ($\beta = .19$, *B* = .39, *p* = .05), behavioral SR ($\beta = .29$, *B* = .23, *p* = .001), and working memory ($\beta = .18$, *B* = .13, *p* = .05) were significantly related to vocabulary. VMS scores were not significantly associated with children's vocabulary performance.

Post-hoc analyses were conducted to further examine the change in variance explained by VMS and the three behavioral SR and EF tasks for significant associations with academic outcomes. Estimates of variance explained were obtained by subtracting the variance accounted for in a model with only covariates from the variance accounted for in models that added the three behavioral SR and EF tasks only, VMS only, or VMS and the three behavioral SR and EF tasks together. After accounting for the ELL status, child gender, child age, and maternal education covariates, the behavioral SR and EF tasks accounted for an additional 11% of the variance in emergent literacy, an additional 18.21% of the variance in mathematics, and an additional 14.33% of the variance in vocabulary. After accounting for covariates, VMS scores alone accounted for an additional 6.02% of the variance in emergent literacy, and an additional 6.63% of the variance in mathematics. After accounting for covariates, including the three behavioral SR and EF tasks and the VMS task together accounted for 12.54% of the variance in emergent literacy and 18.85% of the variance in mathematics, and 14.6% of the variance in vocabulary.

Discussion

Utilizing a sample of prekindergarten and kindergarten age children, the present study used measures of both behavioral SR and EF to examine direct relations with VMS. We also assessed if behavioral SR and EF varied in relation to VMS based on the age of the child in the prekindergarten and kindergarten samples. Finally, we examined how VMS, behavioral SR, and EF uniquely related to academic achievement in spring of the prekindergarten and kindergarten year.

Results supported our first hypothesis, showing a significant relationship between behavioral SR and working memory with VMS, and marginal significance for the inhibitory control task. For our second research question, two interactions were found showing that inhibitory control and working memory (at the trend level) were more related to VMS for younger children. For the final research question, behavioral SR, EF, and VMS were related to academic success, with differential effects for emergent literacy, math, and vocabulary. Behavioral SR, EF (i.e., working memory, inhibitory control), and VMS were all significantly related to emergent literacy. Significant relations were found for VMS and behavioral SR with math, with marginal significance found for inhibitory control with math. Finally, significant relations were found between behavioral SR and EF with vocabulary. These results offer support for an embodied theory of learning during early childhood, with the integration of motor and visual processes (i.e., VMS), behavioral SR, and EF related to higher emergent literacy and math.

Relationship Between Behavioral Self-Regulation, Executive Function, and Visuomotor Skills

The significant and positive relations between working memory, inhibitory control, behavioral SR, and VMS are consistent with work using clinical (Baron et al., 2009) and non-clinical samples (Decker et al., 2011), and lend support to the notion that behavioral SR and EF relate to VMS. Fine motor measures, such as those used in the present study (i.e., VMS), integrate both visual and motor control, with the perceptual demands of these tasks tapping behavioral SR and EF. For example, as the child is presented with a geometric shape, they are first required to focus on the object. These actions integrate attention and inhibitory control, requiring attention to be focused on the task, as inhibitory control restrains the compulsion to start before processing the image. Next, visual-spatial attention, which taps working memory (Störmer, Passow, Biesenack, & Li, 2012), is integrated as the child holds the image in mind and organizes the drawing within the given parameters. As the child moves from one geometric shape to the next, they are required to shift attention, and inhibit incorporating components of the former object into the latter. Finally, each of the above cognitive skills requires the overt regulation of motor actions to carry out the proper behavior.

At the same time, close examination of the standardized effects between the three tasks with VMS showed the strongest relations for behavioral SR. This is the only task in the current study that involves a high level of motor activity, suggesting a possible overlap between visuomotor processing (i.e., VMS) and a task requiring gross motor movements (the HTKS). The size of the standardized coefficients for the inhibitory control and working memory tasks were similar. Both tasks were less related to VMS relative to behavioral SR, lack a motor component, and showed an interaction with age, suggesting they are less related to VMS in older children.

The stronger relationship between behavioral SR with VMS could be due to the overlap between the cortex and motor system (Diamond, 2000). That is, there are anatomical connections between cerebellar and prefrontal cortices (Middleton & Strick, 2002), and evidence showing the cerebellum is active during EF tasks (Strick et al., 2009). At varying levels, given that behavioral SR and VMS contain a motor component, both likely show stronger cerebro-cerebellar connections relative to other measures of EF. There is also evidence for a separate component of EF that specifically processes motor actions and visual related motion (Wood, 2007), and this system could also relate to overt actions requiring behavioral SR. Taken together, results revealed the strongest effect on VMS for behavioral SR, with non-motor EF tasks showing a significant but smaller relationship.

Interactions Between Age, Behavioral Self-Regulation, and Executive Function on Visuomotor Skills

Age is shown to predict performance on VMS tasks (Decker et al., 2011) and is related to growth in the development of EF (Carlson, 2005; Diamond et al., 1997; Rothbart & Posner, 2001). The findings in the present study show age significantly moderated the relationship between inhibitory control and VMS, indicating inhibitory control is more related to VMS in younger children. Correlations in the present sample for age with VMS and inhibitory control were positive, with the interaction suggesting the relationship between VMS and inhibitory control is attenuated for older children who are high on both. This could indicate that at younger ages, better inhibitory control aids performance on a VMS task, possibly allowing children to inhibit starting the task before processing the image. At older ages, better inhibitory control appears to be less related to the demand components of a VMS task.

Experience, age, and the inhibitory demands of a visuomotor task could possibly relate to the age effect. For example, in a study exploring the effects of age and experience on EF and achievement, age was more related to EF relative to experience, with experience (i.e., time in prekindergarten) predicting math and emergent literacy (Skibbe, Connor, Morrison, & Jewkes, 2011). Kindergartners spend more time on academic tasks (e.g., writing letters, numbers), and the increased practice with these types of tasks in the classroom could strengthen VMS. Additionally, exposure to visuomotor tasks is linked to the automaticity of VMS (Floyer-Lea & Matthews, 2004). Given that kindergarteners spend more of the day on fine motor tasks compared to prekindergarteners (Marr, 2003), VMS could start to become automatized in kindergarten. As such, it is possible that as fine motor tasks become automatic less inhibitory control may be needed.

It is also possible that potential ceiling effects in the inhibitory control measure for the kindergarten sample are influencing these results. However when viewing this interaction, it is important to assess results relative to the level of inhibition needed for optimal performance on a visuomotor task within both age groups. Preschoolers will likely have had less exposure to tasks that require them to grip and manipulate a pencil and simultaneously scan, process, hold information in memory, and recreate an image. This lack of experience with visuomotor tasks could indicate inhibitory control plays more of a role in VMS at younger ages, with the automaticity of VMS causing less need for inhibitory control on a visuomotor task.

Relations between working memory and behavioral SR with VMS did not significantly vary by age, but evidence for a similar pattern between age and working memory with VMS emerged at a trend level. Similar to inhibitory control, results suggest that younger children with better working memory are better at processing the image, holding the figure in memory, and translating it to paper, with working memory less related to VMS for older children. Again, age-related improvements in both working memory and VMS (e.g., Decker et al., 2011; Diamond et al., 1997; Skibbe et al., 2011), likely contribute to attenuation between the two at older ages.

Further, although EF is comprised of three main components, they are not completely independent. Miyake et al. (2000) argue that within the general model of EF, inhibitory control could be influencing working memory (Bull & Scerif, 2001). This could suggest the interaction between working memory with VMS partially relates to the connection with inhibitory control. For example, poor inhibitory control could influence working memory on the VMS task by not allowing children to fully process, hold, and recreate the image.

Taken together, relations between EF with VMS suggest variability both by age and by the measure of EF. The non-significant interaction with behavioral SR shows some overlap with VMS in prekindergarten and kindergarten age children and could relate to the motor component within both tasks. Although it appears that the VMS task used in the current study requires some level of EF, the concurrent data preclude conclusions about directionality. It is likely both EF and VMS rely on a common underlying component, which is related to embodied cognition (Moreau, 2012, 2013), and the interconnected relationship between the cerebellum and cortex (Diamond, 2000). For example, through fine motor movements during the writing of numbers and letters, perceptual, motor, and somatosensory systems are engaged. This allows information to be internalized and embodied. Overt actions and the regulation of internal thought are facilitated through EF (Koziol et al., 2012), and this is particularly relevant in the classroom (McClelland et al., 2007). The functional overlap between systems controlling motor activity and EF is present at the level of single neurons (Cisek & Kalaska, 2010), linking brain systems driving VMS, behavioral SR, and EF.

Connections among Visuomotor Skills, Behavioral Self-Regulation, Executive Function, and Achievement

We also explored the unique contribution of VMS, behavioral SR, and EF with measures of vocabulary, literacy, and math achievement. Findings in the present study are consistent with past work and offer new insight into the differential relationships between VMS, behavioral SR, and EF with literacy, math, and vocabulary. When examined together, VMS and the three behavioral SR and EF tasks were uniquely related to emergent literacy, extending previous work by showing that inhibitory control and working memory added unique variance to literacy skills. We also found that behavioral SR and VMS were the only tasks significantly related to math. This extends previous work by showing two tasks with a motor component - one fine motor task and one gross motor task assessing behavioral SR - were significantly related to math achievement.

Emergent literacy, visual motor skills, behavioral self-regulation, and executive function. Both behavioral SR and EF when assessed relative to VMS significantly related to early literacy skills. Together these tasks also accounted for close to 13% of explained variance above the covariates, with VMS alone explaining 6% of the variance in emergent literacy. Taken as a whole, the consistent link found with VMS and literacy could be due to the early writing skills developed in both prekindergarten and kindergarten. For example, a child's ability to write his/her name is highly related to the development of literacy and writing skills (Puranik & Lonigan, 2012; Puranik, et al., 2011). At the level of basic processing, representing one's name with letters through physical movements engages the brain and body, allowing the mind to use the body to process information by tapping perceptual and motor resources. This connection is supported by research in embodied cognition (Balcetis & Cole, 2009; Barsalou, 1999; Boncoddo et al., 2010; Fischer & Zwaan, 2008), with coupling between movement, the body, and EF improving learning for prekindergarten children (Boncoddo et al., 2010). It is possible that children who are more proficient at copying and drawing letters are faster at learning the letters and their sounds, and show heightened internalization of reading concepts leading to better literacy skills (Puranik et al., 2011).

Results also showed both behavioral SR and EF significantly related to emergent literacy skills (Bull et al., 2008; McClelland et al., 2007), with the three tasks alone explaining 11% of the variance in emergent literacy above the covariates. The positive link between behavioral SR, EF, and VMS with literacy could point to a synergistic relationship as reading skills develop. For example, as a child is copying letters and learning letter names and sounds, better EF will augment the processing and storage of the shape, name, and sound of the letter. This will not only highlight properties such as the name and sound, but also improve the geometric representation of the figure in memory, improving VMS by aiding the child as they recreate its shape. This, in turn, could improve how the letter is internally represented, understood, and remembered.

Math, visual motor skills, behavioral self-regulation, and executive function. Consistent with past work, results showed both behavioral SR and VMS significantly related to higher math scores (Cameron et al., 2012; Carlson et al., 2013; McClelland et al., 2007). Although working memory and inhibitory control are found to relate to math (Blair & Razza, 2007; Bull et al., 2008), when the two tasks were assessed concurrently with motor related tasks (behavioral SR, VMS) in the current study, they were not significantly related to math achievement. These results extend previous work by showing that both a visuomotor task and a task requiring gross motor movements relate to higher math scores, which is supported by neuroimaging studies (Bueti & Walsh, 2009; Dehaene, Molko, Cohen, & Wilson, 2004), and suggest embodied cognition could augment academic performance. For example, Bueti and Walsh (2009) argue that motor activity leads to an understanding of quantity and space. It is through walking, running, reaching, or throwing that a child learns to compare distance, size, space, and location. Work with behavioral SR supports this proposal in prekindergarten children, with behavioral SR mediating relations between higher levels of active play with math achievement (Becker et al., 2014).

Further support for Bueti and Walsh (2009) suggests that VMS can be tied directly to the physical body. Numerous studies show wrestlers outperform non-athletes on tasks requiring mental rotation (Moreau, Mansy-Dannay, Clerc, & Guerrién, 2011; Moreau, 2012, 2013), with this performance hindered when the hand is constrained (Moreau, 2012, 2013). Tasks assessing mental rotation are also shown to relate to math performance (Casey, Nuttall, Pezaris, & Benbow, 1995; Casey, Pezaris, & Nuttall, 1992; O'Boyle et al., 2005; Reuhkala, 2001), supporting the link between VMS with math achievement. Although VMS accounted for nearly 7% of explained variance in math, with behavioral SR and EF explaining 18%, VMS are arguably important given the proximal relationship between math relevant visual stimuli and the physical manipulation of math related content. For example, through writing and viewing quantities a child learns one to one correspondence between a number and its value (Zebian, 2005). Most of the additional variance explained by VMS in math overlaps with behavioral SR and EF, suggesting the components of EF and behavioral SR that are tapped by VMS are important for predicting math in the current study.

Vocabulary, visual motor skills, behavioral self-regulation, and executive function. Finally, VMS were not significantly related to vocabulary scores. This could suggest VMS are serving as an intermediary for direct physical learning rather than learning that involves the names of objects. Both behavioral SR and EF, however, were significantly related to children's vocabulary. Significant concurrent relationships are found between receptive vocabulary and EF tasks tapping working memory (Gathercole & Baddeley, 1993), cognitive flexibility (Hongwanishkul, Happaney, Lee, & Zelazo, 2005; Müller, Zelazo, & Imrisek, 2005) and inhibitory control (Blair, 2003). The vocabulary measure used in the current study includes receptive and expressive vocabulary, although the majority of the items tap expressive vocabulary. Research has shown longitudinal associations between receptive and expressive vocabulary, behavioral SR, and EF in preschool (Fuhs & Day, 2011; Weiland, Barata, & Yoshikawa, 2014) and kindergarten (Cameron Ponitz et al., 2009). In the present study, relative to the other measures, we found that behavioral SR showed the strongest relation to vocabulary. Taken together, these results extend previous work on connections between behavioral SR, EF, and VMS with achievement, showing behavioral SR, EF, and VMS contribute unique variance to early literacy skills, with behavioral SR and VMS related to math scores.

Limitations and Future Directions

This study revealed important links between behavioral SR, EF, VMS, and measures of emergent literacy, vocabulary, and math achievement but a number of limitations must be noted. First, given the lack of baseline data due to the fact that measures were taken at one time point, it was not possible to assess directionality. Future work should assess longitudinal connections between the three constructs, examining if better VMS precedes better behavioral SR and EF or if the inverse is true. It is possible that strength in either domain improves the function of the other, with the reciprocal effects relating to achievement. Second, the number of participants was relatively small within the prekindergarten and kindergarten classes, which may have limited our ability to detect significant effects with the full model. Further elucidating the relationship between behavioral SR, EF, and VMS, and assessing if these connections vary by age can offer important insight into why VMS are consistently related to achievement, and should be examined with future studies.

Finally, it is important to extend these results longitudinally to understand connections between behavioral SR and EF with VMS in relation to growth in achievement as a child moves from prekindergarten into grade school. This is particularly relevant given the strong connection between VMS with literacy and math (Cameron et al., 2012; Carlson et al., 2013; Grissmer et al., 2010; McPhillips & Jordan-Black, 2007; Son & Meisles, 2006; Taylor, 1999). It is possible that longitudinal data could show that VMS mediates the relationship between behavioral SR and EF in prekindergarten with early literacy and math skills in kindergarten, which could not be properly assessed with the present data given all measures were taken at one time point. Future research should investigate this possibility.

Conclusions and Implications

Results from this study offer both practical and theoretical implications for teaching and research. First, as illustrated by Diamond (2010), learning needs to address all aspects of development - social, emotional, cognitive, and physical - as each is intertwined. The present paper represents aspects of the latter two, showing relations between VMS with behavioral SR, EF, emergent literacy, and math achievement. At a theoretical level, results are consistent with the idea that cognition is an embodied process, showing a behavioral SR task requiring gross motor movements significantly related to a visuomotor task in prekindergarten- and kindergarten-age children, with both predicting higher math and emergent literacy scores. At the same time, results further elucidate the connection between motor and higher level cortical systems (Diamond, 2000), and could suggest a separate component of EF is involved in both executively driven fine and gross motor actions (Moreau, 2013b; Wood, 2007). A better understanding of the role of motor activity for learning is needed within the age group in the present study, as behavioral SR and EF are demonstrated to be malleable (Diamond, 2012; Tominey & McClelland, 2011), and early visuomotor interventions that tax EF could lead to higher academic achievement. At a classroom level, results showing working memory and inhibitory control relate to VMS at younger ages, with VMS linked to emergent literacy and math in both prekindergarten and kindergarten, could be used to inform teaching strategies for children struggling with early learning. This is important given that fine motor skills can become automatized (Floyer-Lea & Matthews, 2004) with fine motor interventions possibly freeing cognitive resources during learning tasks, which could relate to improved understanding and higher achievement.

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Appendix

Final Models for Each Research Question

The final model for Research Question 1 was estimated as follows:

$$Y_i = B_0 + B_{1i}(\text{maternal education})_i + B_{2i}(\text{ELL status})_i + B_{3i}(\text{child gender})_i + B_{4i}(\text{child age})_i + B_{5i}(\text{inhibitory control})_i + B_{6i}(\text{working memory})_i + B_{7i}(\text{behavioral SR})_i + r_i,$$

where Y_i represents VMS for child i, plus the contributions of maternal education, ELL status, child gender, child age, and the three behavioral SR and EF tasks, plus error.

The final model for Research Question 2 was estimated as follows:

$$Y_i = B_0 + B_{1i}(\text{maternal education})_i + B_{2i}(\text{ELL status})_i + B_{3i}(\text{child gender})_i + B_{4i}(\text{child age})_i + B_{5i}(\text{inhibitory control})_i + B_{6i}(\text{working memory})_i + B_{7i}(\text{behavioral SR})_i + B_{8i}(\text{age*EF/SR interaction})_i + r_i,$$

where Y_i represents VMS for child i, plus the contributions of maternal education, ELL status, and child gender, plus the main effects for child age and the three EF tasks, and the interaction between child age and the behavioral SR or EF task score of interest (working memory, inhibitory control, behavioral SR), plus error.

The final model for Research Question 3 was estimated as follows:

$$Y_i = B_0 + B_{1i}(\text{maternal education})_i + B_{2i}(\text{ELL status})_i + B_{3i}(\text{child gender})_i + B_{4i}(\text{child age})_i + B_{5i}(\text{inhibitory control})_i + B_{6i}(\text{working memory})_i + B_{7i}(\text{behavioral SR})_i + B_{8i}(\text{VMS})_i + r_i,$$

where Y_i represents the academic outcome of interest (emergent literacy, mathematics, vocabulary) for child i, plus the contributions of maternal education, ELL status, child gender, and child age, plus the main effects for the three EF tasks and VMS, plus error.

Table 1

Descriptive Statistics

	ELL Status	Child Gender	Child Age	Maternal Education	VMS	Inhibitory Control	BSR	Working Memory	Emergent Literacy	Mathematics	Vocabulary
Overall:											
N	123	127	127	100	118	122	121	115	121	113	122
Mean	.07	.46	68.55	15.55	15.11	27.24	33.20	468.32	387.09	437.87	477.02
SD	.23	.50	7.75	3.32	3.38	7.34	19.23	21.17	48.66	24.23	15.59
Min - Max	0 - 1	0 - 1	53 - 80	6 - 21	3 - 21	0 - 32	0 - 59	425 - 512	276 - 514	350 - 481	423 - 513
Prekindergarten:											
N	45	49	49	38	42	44	43	41	46	38	44
Mean	.11	.45	59.88	14.13	12.29	23.75	15.28	451.44	345.15	416.05	466.91
SD	.32	.50	3.43	3.87	3.13	9.60	16.70	15.70	29.31	23.13	16.49
Min - Max	0 - 1	0 - 1	53 - 67	6 – 19.5	3 - 18	0 - 32	0 - 49	425 - 490	276 - 446	350 - 467	423 - 491
Kindergarten:											
N	78	78	78	62	76	78	78	74	75	75	78
Mean	.04	.47	74	16.41	16.67	29.21	43.09	477.67	412.81	448.92	482.72
SD	.19	.50	3.59	2.62	2.35	4.72	12.06	17.79	39.40	15.89	11.79
Min - Max	0 - 1	0 - 1	68 - 80	11.5 - 21	9 - 21	6 - 32	0 - 59	433 - 512	354 - 514	403 - 481	460 - 513

Note. ELL = English Language Learner; 0 = no, 1 = yes. Child Gender: 0 = female, 1 = male. Child Age = in months. BSR = Behavioral Self-Regulation. VMS = Visuomotor Skills.

Table 2

Bivariate Pairwise Correlations Between Variables

	Correlations							
Variable	1	2	3	4	5	6	7	8
1. Child Age (in months)	-	-	-	-	-	-	-	-
2. Maternal Education (in years)	.35*	-	-	-	-	-	-	-
3. VMS	.60*	.37*	-	-	-	-	-	-
4. Inhibitory Control	.38*	.30*	.43*	-	-	-	-	-
5. Behavioral SR	.67*	.49*	.60*	.44*	-	-	-	-
6. Working Memory[a]	.54*	.42*	.53*	.31*	.61*	-	-	-
7. Emergent Literacy[a]	.64*	.49*	.62*	.46*	.66*	.60*	-	-
8. Mathematics[a]	.62*	.46*	.59*	.50*	.74*	.56*	.71*	-
9. Vocabulary[a]	.48*	.55*	.46*	.42*	.60*	.50*	.64*	.63*

Note. Behavioral SR = Behavioral Self-Regulation. VMS = Visuomotor Skills.
[a] W score.
* $p < .05$.

Table 3

Behavioral Self-Regulation and Executive Function Tasks Predicting Visuomotor Skills

Variable	*B*	*SE*	β
ELL Status	-.51	1.36	-.04
Child Gender	.03	.35	.00
Child Age	.11†	.06	.26
Maternal Education	.05	.06	.05
Inhibitory Control	.07†	.04	.15
Working Memory	.02*	.01	.14
Behavioral SR	.05*	.02	.28

Note. Behavioral SR = Behavioral Self-Regulation. *B* = Unstandardized Estimate. *SE* = Standard Error. β = Standardized Estimate.
$^{\dagger}p < .10$. $^{*}p < .05$.

Table 4

Interactions Between Behavioral Self-Regulation, Executive Function and Child Age Predicting Visuomotor Skills

	Age*Inhibitory Control Interaction Model			Age*Working Memory Interaction Model			Age*Behavioral SR Interaction Model		
Variables	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*
ELL Status	-.57	1.31	-.04	-.32	1.42	-.02	-.33	1.39	-.02
Child Gender	-.03	.28	-.00	-.06	.30	-.01	.04	.33	.01
Child Age	.11*	.06	.26	.10†	.06	.24	.11†	.06	.25
Maternal Education	.06	.06	.06	.05	.06	.05	.05	.06	.05
Inhibitory Control	.00	.04	.01	.07†	.04	.15	.07†	.04	.15
Working Memory	.02*	.01	.16	.03*	.01	.17	.02*	.01	.14
Behavioral SR	.05†	.02	.26	.04†	.02	.23	.04†	.02	.26
Age*Inhibitory Control	-.01*	.00	-.24	-	-	-	-	-	-
Age*Working Memory	-	-	-	-.00†	.00	-.11	-	-	-
Age* Behavioral SR	-	-	-	-	-	-	-.00	.00	-.06

Note. Behavioral SR = Behavioral Self-Regulation. *B* = Unstandardized Estimate. *SE* = Standard Error. β = Standardized Estimate.
$^{\dagger}p < .10$. $^{*}p < .05$.

Table 5

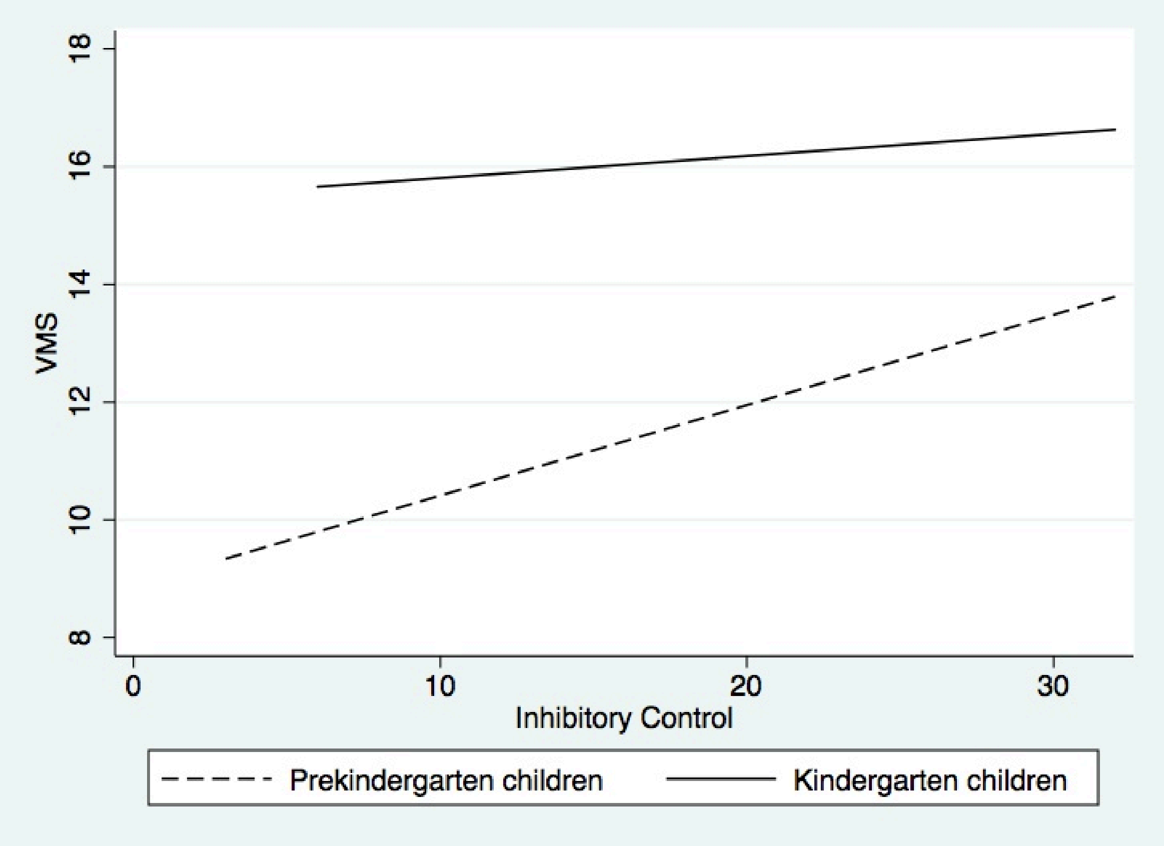
Behavioral Self-Regulation, Executive Function, and Visuomotor Skills Predicting Academic Outcomes

	Emergent Literacy			Mathematics			Vocabulary		
Variable	*B*	*SE*	β	*B*	*SE*	β	*B*	*SE*	β
ELL Status	3.27	13.57	.02	-14.77†	8.20	-.16	-3.75	6.16	-.06
Child Gender	7.39	6.29	.08	7.15*	2.24	.16	4.36*	1.43	.14
Child Age	1.29*	.58	.21	.29*	.13	.10	.07	.19	.04
Maternal Education	1.87	1.33	.12	.51	.56	.07	.84†	.48	.17
Inhibitory Control	.83*	.29	.13	.41†	.22	.13	.39*	.17	.19
Working Memory	.50*	.10	.22	.12	.09	.12	.13*	.06	.18
Behavioral SR	.39*	.18	.16	.49*	.10	.42	.23*	.06	.29
VMS	2.65*	1.09	.18	.88*	.44	.13	.14	.48	.03

Note. Behavioral SR = Behavioral Self-Regulation. VMS = Visuomotor Skills. *B* = Unstandardized Estimate. *SE* = Standard Error. β = Standardized Estimate.
$^{\dagger}p < .10$. $*p < .05$.

Figure 1

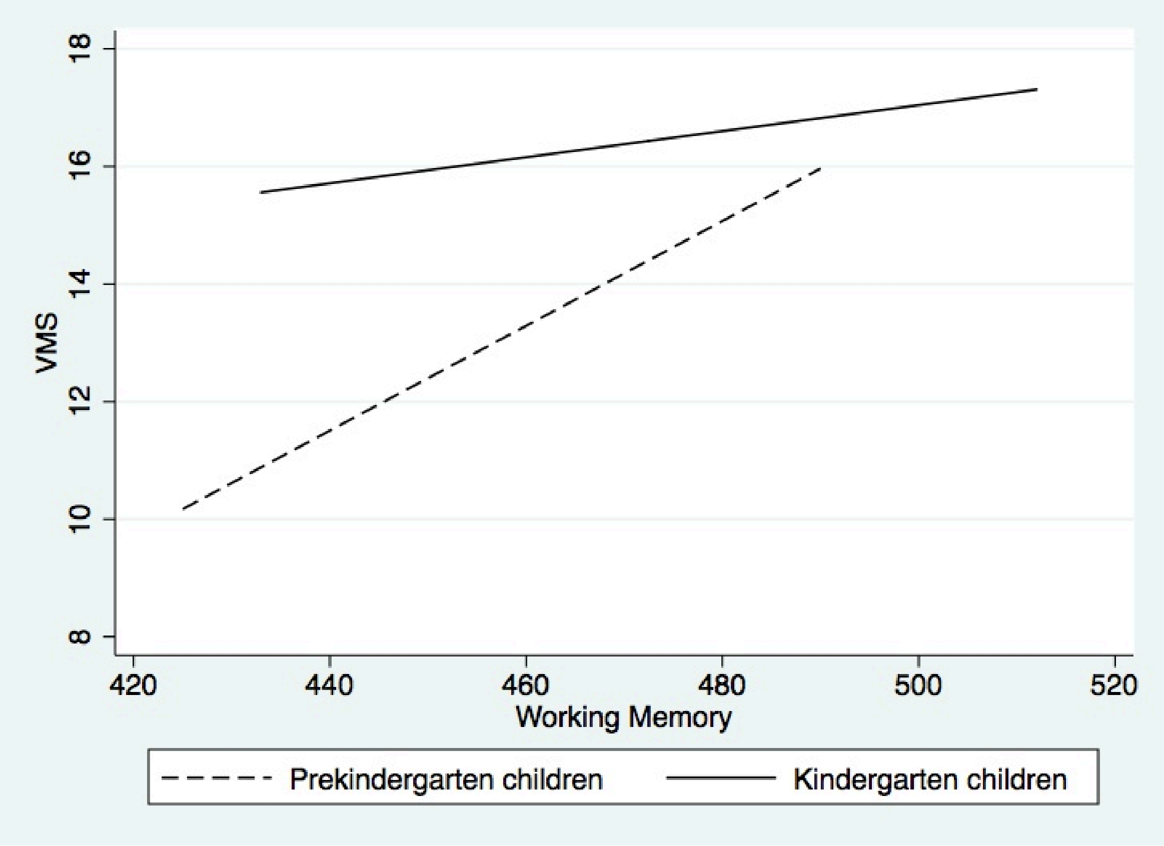
Interaction Between Child Age and Inhibitory Control Predicting Visuomotor Skills



Note. VMS = Estimated visuomotor skills raw score on VMI task. Inhibitory Control = Sum score on Day-Night task. Covariates included in estimated VMS scores.

Figure 2

Interaction Between Child Age and Working Memory Predicting Visuomotor Skills



Note. VMS = Estimated visuomotor skills raw score on VMI task. Working Memory = W-score on Woodcock-Johnson Auditory Working Memory task. Covariates included in estimated VMS scores.