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Research paper

Unique and compensatory associations of executive functioning and visuomotor integration with mathematics performance in early elementary school

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ABSTRACT

Research has illuminated contributions—usually modeled separately—of both executive functioning (EF) and visuomotor integration (VMI) to mathematical development in early elementary school. This study examined simultaneous associations of EF and VMI, measured at the beginning of the school year, with concurrent and later mathematics performance on several mathematics assessments in kindergartners (n = 89, M_{age} = 5.5 years) and first graders (n = 73, M_{age} = 6.6 years) of low socioeconomic status. Both skills were related to concurrent performance on all assessments, as well as improvement through the end of the school year for all but a geometry subtest, which was predicted only by VMI. No significant influence of an interaction between the skills was present, except for concurrently on the geometry subtest and longitudinally on an assessment with a relatively strong emphasis on informal skills. Findings are discussed in the context of supporting mathematics development in early childhood.

1. Introduction

Children's early mathematics ability is an important factor supporting academic success (e.g., Duncan et al., 2007), but other less explicitly academic skills, when measured in early childhood, are also strongly associated with later academic outcomes (Heckman, Stixrud, & Urzua, 2006). Executive functioning (EF) and visuomotor integration (VMI) upon school entry are two such skills, especially in the way they support mathematics learning (Cragg & Gilmore, 2014; Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014). Each of these skills shows consistent associations with later mathematics outcomes (e.g., Blair & Razza, 2007; Newcombe & Frick, 2010) and theory has independently been developed for each skill regarding why each might support academic achievement and mathematics achievement in particular. However, despite these skills appearing to co-develop in early childhood (see Cameron, Cottone, Murrah, & Grissmer, 2016), studies linking them to mathematics performance have often considered them in isolation. Thus, whether each skill makes a unique contribution to mathematics performance when the other is measured is less well understood, as is whether strengths in one skill might compensate for relative weaknesses in the other. Even less understood is whether such contributions are consistent across different types of mathematics assessments.

Understanding the contributions of cognitive skills to academic outcomes may be especially important in populations with low socioeconomic status (SES; i.e., racial minority status and/or of low-income), who are traditionally considered at-risk for school difficulties. This heightened risk can, in part, be explained by fewer opportunities for children of low socioeconomic status to fully develop the cognitive skills which promote academic adjustment and performance (Bradley & Caldwell, 2013; Verdine, Golinkoff et al., 2014).

This study examines both EF and VMI as predictors of concurrent mathematics performance and improvement in several measures of mathematics performance over the course of one school year in a sample of mostly African-American kindergarteners and first graders from low-income families. Based on research with preschool-age children (Cameron et al., 2015), compensatory effects – by which strengths in one skill counteract effects of short-comings in the other – between EF and VMI were also tested.

1.1. EF and academic performance

EF is a cognitive construct typically described as the higher cognitive processes underlying conscious control of thought and action

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(Jacques & Marcovitch, 2010). These processes fall into correlated but distinct components: working memory, cognitive flexibility, and inhibitory control (Diamond, 2013; Miyake et al., 2000). In this study, EF was measured using a composite from multiple tasks.

Development in EF is characterized by several periods of rapid growth, particularly during early childhood (Diamond, 2006; Romine & Reynolds, 2005). Early overall EF, as well as specific components of EF, are linked to a wide range of academic and life outcomes from preschool through adulthood (Diamond, 2013; McClelland, Acock, Piccinin, Rhea, & Stallings, 2013). For instance, McClelland et al. (2007) found that incoming EF in preschool was correlated with initial academic skills but also predicted preschoolers' math and literacy improvements by the end of preschool. EF is also associated with academic achievement in math and literacy after children transition to kindergarten (Ponitz, McClelland, Matthews, & Morrison, 2009), even after controlling for IQ (Blair & Razza, 2007). The association between preschool EF and academic skills is consistent at least through college (Duncan et al., 2007; McClelland et al., 2013).

Beyond facilitating appropriate classroom engagement, EF supports specific academic tasks, especially in mathematics (Geary, 2011; Willoughby, Blair, Wirth, & Greenberg, 2012). For example, children with low inhibitory control − one component of EF − may be less likely to evaluate and switch mathematical problem-solving strategies when they prove ineffective (Bull & Scerif, 2001). EF seems to be particularly important for word problems, which require students to build and manipulate models of the problems in their heads (Fuchs et al., 2010a, 2010b).

Empirical evidence confirms that EF undergirds performance on mathematical tasks, with many studies demonstrating their concurrent and longitudinal links. For instance, both overall EF and specific components of EF are known to longitudinally predict mathematics performance in early childhood (Clark, Sheffield, Wiebe, & Epsy, 2013), early elementary school (Geary, 2011), and middle elementary school (LeFevre et al., 2013). Numerous studies demonstrate that EF, and especially working memory, accounts for significant variance in mathematics performance above and beyond other potential confounds, including prior mathematics performance, language skills, and even IQ (see Cragg & Gilmore, 2014 for a review). Recent studies have even suggested that EF may, at least partially, mediate the relationship between SES and mathematics outcomes (Dilworth-Bart, 2012) and researchers have suggested that promoting EF as part of encouraging children to develop adaptive self-regulatory strategies could be a viable means to improve the academic outcomes of children from low-SES families (Ursache, Blair, & Raver, 2012).

1.2. VMI and academic performance

VMI is considered an aspect of visuospatial processing and, like EF, is a complex process requiring integration of multiple skills, namely, visual and motor functioning (Beery & Buktenica, 1997). The most prominently used measures of VMI are design-copying tasks, in which individuals are typically asked to copy a series of increasingly complex figures. While copying a design may seem like a fairly simple task, it requires several component skills, chief among them the ability to parse a whole figure into its parts and to reintegrate those parts into a whole (Akshoomoff & Stiles, 1995).

The development of VMI, which is preceded by development of more rudimentary visual and motor skills prior to their integration develops rapidly during early childhood (ages 4 through 7 years), but continues through at least age 12 (Decker, Englund, Carboni, & Brooks, 2011). Past research drew attention to visuospatial skills in general, and VMI in particular, by documenting links between early "visuospatial" or "fine motor" skills and later academic achievement (e.g., Cameron et al., 2012; Carlson, Rowe, & Curby, 2013; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Luo, Jose, Huntsinger, & Pigott, 2007; Stevenson & Newman, 1986). These studies' measures often included design-copying tasks, which as mentioned above are elsewhere and in this study are considered measures of VMI (e.g., Beery & Buktenica, 1997, Korkman, Kirk, & Kemp, 1998). As discussed next, several studies document links of VMI with mathematics performance, specifically.

Developmental theory and research has long highlighted the notion that basic mathematical competencies (e.g., concepts of number) are directly dependent upon visuospatial development. Indeed, mathematical tasks in the classroom (e.g., estimating the number of objects in a jar, measuring the length of an object, copying diagrams from the board) often require visuospatial skills and VMI. Further, research in cognitive neuroscience points to a neural basis for the link between visuospatial skills and mathematical abilities. Dehaene and Cohen (2007) suggest that the neural machinery supporting humans' sophisticated visual spatial processing abilities may be "recycled" to form powerful visual representations of mathematical concepts (e.g., as in the development of a mental number line; Dehaene, 2011).

Empirical evidence has also documented links between visuospatial skills and mathematics development in children. In two studies of early elementary school students, one with a low-SES sample, and the other with a middle-SES sample, Gunderson, Ramirez, Beilock, and Levine (2012) found that children's visuospatial skills predicted later number line knowledge and calculation skills, even after controlling for prior number line knowledge and math ability. While these findings are what one might expect given work linking visuospatial skills with the mental number line in adults (e.g. Doricchi, Guariglia, Gasparini, & Tomaiuolo, 2005), it is also possible that EF was a confound in these relationships, as it was not measured. Although visuospatial skills and EF are distinct cognitive processes, any task that requires attentional resources and problem solving will also utilize EF (Korkman et al., 1998), and visuospatial skills tasks are no exception. Indeed, at least one study has found that the association between VMI and mathematics does not hold after controlling for certain measures of attention, which are considered an aspect of EF (Sortor & Kulp, 2003). Therefore, it is important to measure EF when examining visuospatial (and VMI) skills' unique contribution to early math skills, and vice versa. Further, because children from low-income households tend to have nascent visuospatial skills early in elementary school (Potter, Mashburn, & Grissmer, 2013), it may be particularly important to understand to what extent this ability contributes to mathematics performance in a sample of children from low-SES families.

1.3. Unique contributions of EF and VMI to mathematics performance

EF and visuospatial skills in general, and VMI in particular, may exhibit co-dependency in development and may interact in nuanced ways to support children's adaptation in school (Assel, Landry, Swank, Smith, & Steelman, 2003; Cameron et al., 2016). Ample evidence exists to support the notion that EF is an important promotive factor for school success and mathematics performance in particular, above and beyond other potential confounds, such as intelligence (see Cragg & Gilmore, 2014 for a review). Less research has focused on whether apparent contributions of visuospatial ability in general, and VMI in particular, to mathematics performance remain after accounting for other cognitive skills such as EF. Thus, while there is reason to suspect that EF should predict mathematics performance even when accounting for visuospatial skills, such as VMI, it is less clear that the converse is true (i.e., that VMI should predict mathematics performance after accounting for EF).

Two studies utilizing teacher reports for EF found unique associations between visuospatial skills and mathematics performance. Assel et al. (2003) measured visuospatial skills, in part, with a design-copying task and EF using teacher report at ages three, four, and six; and mathematics ability at age eight in low- to lower-middle-SES children. They found that both predictors were highly correlated from one time point to another (i.e., visuospatial skills to visuospatial skills and EF to EF) and that visuospatial skills and teacher-rated EF at age six were