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Brief Report

Early numerical foundations of young children's mathematical development

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ABSTRACT

This study focused on the relative contributions of the acuity of the approximate number system (ANS) and knowledge of quantitative symbols to young children's early mathematical learning. At the beginning of preschool, 191 children (M_{age} = 46 months) were administered tasks that assessed ANS acuity and explicit knowledge of the cardinal values represented by number words, and their mathematics achievement was assessed at the end of the school year. Children's executive functions, intelligence, and preliteracy skills and their parents' educational levels were also assessed and served as covariates. Both the ANS and cardinality tasks were significant predictors of end-of-year mathematics achievement with and without control of the covariates. As simultaneous predictors and with control of the covariates, cardinality remained significantly related to mathematics achievement, but ANS acuity did not. Mediation analyses revealed that the relation between ANS acuity and mathematics achievement was fully mediated by cardinality, suggesting that the ANS may facilitate children's explicit understanding of cardinal value and in this way may indirectly influence early mathematical learning.

Introduction

There is vigorous debate over the cognitive foundations of children's early mathematical learning. One hypothesis is that the approximate number system (ANS)—an inherent system for representing

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and processing nonsymbolic quantities (e.g., the quantity of collections of items; see Feigenson, Dehaene, & Spelke, 2004)—provides this early foundation. Indeed, two recent meta-analyses revealed modest but significant relations ($r \sim .20$) between performance on ANS tasks and mathematics achievement (Chen & Li, 2014; Fazio, Bailey, Thompson, & Siegler, 2014), although the relation appears to be stronger before ($r = .40$) rather than after ($r = .17$) children begin formal mathematics instruction (Fazio et al., 2014). Chen and Li's (2014) meta-analysis revealed that the relation between performance on ANS measures and mathematics achievement remained significant with control of intelligence and other domain-general abilities. A related issue is the relative importance of ANS acuity to early mathematics achievement as compared with the importance of young children's other quantitative competencies.

These other foundational competencies include children's early symbolic understanding of the quantities represented by number words, numerals, and the relations among them. In fact, several studies suggest that these basic symbolic competencies are the foundation for children's early mathematical development, not ANS acuity (e.g., Bugden & Ansari, 2011; De Smedt & Gilmore, 2011; Iuculano, Tang, Hall, & Butterworth, 2008; Rousselle & Noël, 2007). It is also possible, of course, that both ANS acuity and an understanding of number symbols independently contribute to mathematics achievement (e.g., Fazio et al., 2014) or that one of the two mediates the other's relation to mathematics achievement (vanMarle, Chu, Li, & Geary, 2014).

In any case, the debate remains unresolved, in part, because the studies to date have assessed ANS acuity and symbolic knowledge using different measures, sometimes with and sometimes without a simultaneous measurement of both types of knowledge, with children at different ages and varying degrees of formal schooling, and with varying degrees of control of potential third-variable confounds (for a review, see De Smedt, Noël, Gilmore, & Ansari, 2013; see also Chen & Li, 2014). Resolution of the debate will require studies that simultaneously assess ANS acuity and core symbolic knowledge in children at the early stages of formal mathematical learning, when the relation between ANS acuity and mathematics achievement is particularly strong (Fazio et al., 2014), and with control of other factors that also influence this learning, specifically executive functions, intelligence, and parental background (Clark, Pritchard, & Woodward, 2010; Geary, 2011; LeFevre et al., 2010).

The choice of ANS and symbolic knowledge tasks is also critical to resolving the debate. The ANS task developed by Halberda and colleagues is based on current theory regarding the functioning of this inherent system and associated performance measures, as noted, are correlated with young children's mathematics achievement (see Bonny & Lourenco, 2013; Halberda, Mazzocco, & Feigenson, 2008; Libertus, Halberda, & Feigenson, 2011; Mazzocco, Feigenson, & Halberda, 2011a, 2011b; Starr, Libertus, & Brannon, 2013; vanMarle et al., 2014). The most appropriate measure of children's emerging symbolic knowledge is less clear. This is because young children's competencies include emerging knowledge of number words and Arabic numerals (Bullock & Gelman, 1977; Condry & Spelke, 2008; Fuson, 1988; Siegler & Robinson, 1982), counting (Briars & Siegler, 1984; Gelman & Gallistel, 1978), cardinality (Sarnecka & Carey, 2008; Wynn, 1992), ordinality (Brainerd, 1979; Brannon & Van de Walle, 2001), and arithmetic (Levine, Huttenlocher, & Jordan, 1992; Starkey, 1992). Of these, number words are the first mathematical symbols that most children learn, and understanding the quantities represented by these symbols is among their first conceptual insight in formal mathematics. vanMarle and colleagues (2014) found that children's understanding of the cardinal value of number words explained approximately 50% of the individual differences in 3- and 4-year-olds' mathematics achievement. For this reason, we suggest that children's understanding of the cardinal value of number words is a suitable symbolic knowledge contrast to ANS acuity.

Our goal was to provide some clarity to the debate by comparing and contrasting the contributions of children's ANS acuity and understanding of the cardinal value of number words at the beginning of preschool and their mathematics achievement at the end of the academic year. We controlled for executive functions, intelligence, parental education, and preliteracy skills; the latter was included because it is correlated with early mathematics achievement and may be a proxy for informal parental instruction before the beginning of preschool (Sénéchal & LeFevre, 2002).