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Early number knowledge and cognitive ability affect early arithmetic ability

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ABSTRACT

Previous literature suggests that early number knowledge is important for the development of arithmetic calculation ability. The domain-general ability of verbal working memory also has an impact on arithmetic ability. This longitudinal study tested the impact of early number knowledge and verbal working memory on the arithmetic calculation ability of children in preschool ($N = 315$) and then later in Grade 1 using structural equation modeling. Three models were used to test hypotheses drawn from previous literature. The current study demonstrates that both early number knowledge and the domain-general ability of verbal working memory affect preschool and Grade 1 arithmetic ability. Early number knowledge had a direct impact on the growth of arithmetic ability, whereas verbal working memory had only an indirect effect via number knowledge and preschool arithmetic ability. These results fit well with von Aster and Shalev's developmental model of numerical cognition (*Developmental Medicine & Child Neurology*, 2007, *Vol. 49*, pp. 868–873) and highlight the importance of considering arithmetic ability as independent from early number knowledge. Results also emphasize the importance of training early number knowledge before school entry to promote the development of arithmetic ability.

Introduction

Competence in mathematics is important for children in educational settings (Duncan et al., 2007) and for many aspects of everyday adult life (e.g., paying bills, understanding information such as per-

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centages; Every Child a Chance Trust, 2009; McCloskey, 2007). Thus, children and adults who do not learn basic mathematical skills (e.g., the ability to calculate) are potentially disadvantaged in relation to their peers. Following this line of reasoning, a theoretically important research task is to identify the foundational abilities or cognitive conditions that support early learning of arithmetic in a child's academic career. More knowledge about this area would also be helpful for educational purposes, for example, when developing programs aimed at enhancing the mathematical skills of preschool children (Jordan, Glutting, & Ramineni, 2010). The current study focused on two foundational cognitive domains, the domain-specific abilities related to early number knowledge and the domain-general cognitive ability of verbal working memory, and their relation to children's early arithmetic skill. To date, few studies have examined the relative contributions of these two cognitive domains with regard to early arithmetic skill.

Domain-specific early number knowledge

The concept of early number knowledge relates to children's knowledge of numerosity (i.e., cardinality) as well as the relation between numbers (i.e., ordinality), counting words, and Arabic digits (i.e., symbolic knowledge). In previous studies, these abilities have sometimes been incorporated into the term "number sense" (cf. Berch, 2005; National Mathematics Advisory Panel, 2008). However, to use number sense in that context creates conceptual confusion given that it originated from the neurocognitive science area to refer to the highly innate abilities of nonverbally representing and processing numbers, which are core abilities that may serve as a basis for learning arithmetic (Dehaene, 2011; Piazza, 2010; Pica, Lemer, Izard, & Dehaene, 2004; Wilson & Dehaene, 2007). The current study, therefore, avoids the term number sense and instead uses the term "early number knowledge" (or number knowledge).

Number knowledge can be divided into the following two classes of abilities: primary biological and secondary biological (Geary, 1995; Jordan & Levine, 2009). Two primary abilities are the approximate number system (ANS), which is a system for number representation, and the object tracking system (OTS). The ANS represents nonsymbolic numbers in an approximate way on a mental number line with no upper limit, whereas the OTS represents small numbers (<5) in a distinct and exact way (Piazza, 2010).

These primary abilities develop informally and might not require deliberate practice. The secondary biological abilities are, for example, counting words, symbolic numerical comparison, linear representation of symbolic numbers, and (of course) arithmetic operations. These kinds of abilities require deliberate practice to develop. One model of the development of number knowledge is von Aster and Shalev's (2007) hierarchical four-step developmental model of numerical cognition. In this model, an innate, spatially oriented number line (Step 1) develops through the acquisition of number words (Step 2) and Arabic numerals (Step 3), which are then mapped onto the ANS, resulting in a symbolic mental number line (Step 4), which in turn constitutes a precondition for developing more advanced mathematical abilities. A main assumption of this model is that the acquisition of the symbolic system (Steps 2 and 3) and the establishment of the symbolic mental number line (Step 4) are supported by domain-general cognitive abilities such as attention, executive functions, language, and working memory. Empirical findings in line with this notion of domain-general abilities supporting the development of the mental number line have been found when studying the development of children with mathematical learning disabilities (Geary, Hoard, Nugent, & Byrd-Craven, 2008). Empirical evidence also suggests that working memory plays a supporting role in the mapping between the ANS and the verbal number system (Mazzocco, Feigenson, & Halberda, 2011). The current study was theoretically based on this view of the development of numerical cognition but focused on Steps 2, 3, and 4 of the proposed model.

The current practice among researchers is to predict mathematical achievement using different aspects of early number knowledge that are combined into one measure (e.g., Geary, Bailey, & Hoard, 2009; Jordan et al., 2010; Malofeeva, Day, Saco, Ciancio, & Young, 2004). A number of studies that have used an aggregated measure of early number knowledge or multiple separate tasks have shown that early number knowledge measured before school entry (kindergarten) predicts school-age performance on arithmetic tasks even when controlling for general cognitive abilities such as working mem-