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Early developmental trajectories of number knowledge and math achievement from 4 to 10 years: Low-persistent profile and early-life predictors

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ABSTRACT

Little is known about the development of number knowledge (NK) and the antecedents of low-persistent NK profiles in early childhood. We documented the developmental trajectories of NK across the transition from preschool to elementary school, their predictive validity with respect to later math achievement, and the child and family early-life factors associated with low NK profiles. Children's NK was assessed four times at regular intervals between the ages 4 and 7 years in a large, representative population-based sample. Developmental trajectories of NK were established for 1597 children. These children were also assessed with respect to several features of their family environment at 5, 17, and 29 months, as well as their cognitive skills at age 41 months. Analyses revealed a best-fitting 4-trajectory model, characterized by Low-Increasing (10% of the children), Moderate-Increasing (39%), Moderate-Fast Increasing (32%) and High-Increasing (19%) groups. Children of these trajectory groups differed significantly with respect to math achievement at ages 8 and 10 years, with the Low-Increasing group persistently scoring lower than the other groups throughout these years. Children of Low-Increasing NK group were from household of lower income and father with low educational background, poorer early cognitive development, and more importantly, reduced visual-spatial skills and memory-span. Children displaying reduced cognitive abilities and impoverished living conditions early in life are at greater risk of low NK throughout late preschool and school entry, with ensuing difficulties in math achievement. They deserve early preventive attention to help alleviate later mathematic difficulties.

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Knowledge and skills in mathematics have been shown to predict later academic achievement (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Magnuson, Duncan, Lee, & Metzger, 2016; National Research Council, 2009; Nguyen et al., 2016; Siegler et al., 2012), and more generally, later educational attainment (Magnuson et al., 2016). Mathematic abilities are paramount for college entry (Sadler & Tai, 2007) and degree completion in STEM fields (science, technology, engineering and mathematics; Wolniak, 2016). Unfortunately, the negative side of this predictive association is that individuals with poor mathematic abilities have reduced educational and employment opportunities (e.g., low rates of full-time employment and promotions, high rates of low-paying occupations; Lundetræ, Gabrielsen, & Mykletun, 2010; Parsons & Bynner, 1997), and might even experience difficulties in common day-to-day activities in adulthood.

The early signs of these difficulties are quite prevalent. For instance, between 6% and 10% of children suffer from learning disabilities in mathematics (Barbaresi, Katusic, Colligan, Weaver, & Jacobsen, 2005; Shalev, Auerbach, Manor, & Gross-Tsur, 2000), and many more struggle with mathematics without a formal diagnosis. Children showing persistent difficulties in math may never catch up to their grade-level peers. There is also good evidence that these difficulties emerge quite early, even before school entry (Mazzocco & Thompson, 2005; von Aster & Shalev, 2007).

1. Early development of mathematic skills

Children develop a broad array of early mathematic skills well before school entry (Libertus, Feigenson, & Halberda, 2011). As early as 6 months, they possess an intuitive impression of numbers – a number sense – that allows them to approximate magnitude difference between small set of objects (e.g., 4 vs. 8; Feigenson, Dehaene, & Spelke, 2004; Hyde & Spelke, 2011; Lipton & Spelke, 2003; McCrink & Wynn, 2007; vanMarle, 2013; Xu, Spelke, & Goddard, 2005). Number sense is assumed to provide the basic meaning of number and quantity in infancy (von Aster & Shalev, 2007). From these initial number sense skills, children learn counting through linking numbers to objects. Children's numerical development is thus characterized by an increasing capacity to solve mathematic problems using tangible materials (e.g., blocks). Around age 3 years, children typically learn number words, counting principles (e.g., one-to-one counting, cardinality, ordinal number, numerical identification; Bermejo, 1996), and to carry out simple operations (e.g., number combinations, see Geary, 2004, for a review). This early knowledge about numbers is key to later mathematical development (Duncan et al., 2007; Göbel, Watson, Lervåg, & Hulme, 2014; National Research Council, 2009; Nguyen et al., 2016; Watts, Duncan, Siegler, & Davis-Kean, 2014).

Number knowledge (NK), that is, the conceptual and procedural understanding of whole numbers (Okamoto & Case, 1996), has been posited to develop steadily and gradually throughout early childhood (Piaget, 1977), and to lead to more sophisticated mathematic abilities (Duncan et al., 2007; Göbel et al., 2014; National Research Council, 2009; Nguyen et al., 2016; Watts et al., 2014). Specifically, it has been suggested that early NK partially originates from an integration of number sense skills and the symbolic numerical system taught at home or in school (Feigenson, Libertus, & Halberda, 2013; Libertus et al., 2011). Number sense skills, such as subitizing and approximating would prepare children to associate quantities with Arabic digits (i.e., numeral symbols, such as 0, 1, 2 or 3; von Aster & Shalev, 2007). This, in turns, leads to hierarchically order numbers, a stepping-stone in children's mastering of numbers and growing math abilities (Friso-van den Bos et al., 2015; Siegler & Booth, 2004).

Thus, there is both theoretical and empirical support for the view that early NK and the ensuing mathematic skills are developmentally interlocked (Duncan et al., 2007; Göbel et al., 2014; National Research Council, 2009; Nguyen et al., 2016; Piaget, 1977; Watts et al., 2014). However, very little is known about individual differences in the development of these skills. If the development from NK to mathematics generally follows age and grade levels, the rate at which children transit through this period may differ significantly; some children quickly master mathematic concepts and operations while others struggle.

Documenting early NK skills is especially crucial during the transition from late preschool to school entry, as this period is characterized by substantial developmental changes. This transition not only coincides with shifts in physical, cognitive, emotional, and behavioral capacities (Blair & Raver, 2015; Sasser, Bierman, & Heinrichs, 2015; Welsh, Nix, Blair, Bierman, & Nelson, 2010), but it also entails a modification of the learning context, as children start to be systematically exposed to formal training in early mathematic skills. Accordingly, one goal of the present study is to assess inter-individual variations in trends of NK development across the period from late preschool to school entry.

1.1. Early cognitive correlates of number knowledge

An important related question to that of early individual differences in NK is the issue of their associated cognitive factors and putative environmental determinants. Previous studies of normative samples, as well as of low math achievers and children with mathematic learning disability have consistently revealed that poor language, visual-spatial skills, and memory-span are correlates, if not precursors of low math skills (Bull, Espy, & Wiebe, 2008; Dehaene, Piazza, Pinel, & Cohen, 2003; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Geary, 2004; Geary, 2011; Geary, Hoard, Byrd-Craven, & DeSoto, 2004; LeFevre et al., 2010; Mazzocco & Thompson, 2005; Soto-Calvo, Simmons, Willis, & Adams, 2015). Language is involved when manipulating information within working memory, as well as when counting forward and backward. Difficulties in processing numbers have been associated with reading difficulties, language impairment, or both (Jordan, Hanich, & Kaplan, 2003). Clearly, the phonetic and semantic systems are activated when counting, if only to connect the quantities with number words (Vukovic & Lesaux, 2013), and to solve arithmetic problems (Jordan et al., 2003). Deficits in these systems might result in difficulties in counting and arithmetic reasoning, as well as in concurrent reading difficulties (Dehaene & Cohen, 1995, 1997). The visual-spatial system is also solicited when representing conceptual knowledge; visual-spatial skills are indeed involved in basic geometry problems, in magnitude comparisons (Dehaene et al.,

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