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Profiles of children's arithmetic fact development: A model-based clustering approach

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ABSTRACT

The current longitudinal study tried to capture profiles of individual differences in children's arithmetic fact development. We used a model-based clustering approach to delineate profiles of arithmetic fact development based on empirically derived differences in parameters of arithmetic fact mastery repeatedly assessed at the start of three subsequent school years: third, fourth, and fifth grades. This cluster analysis revealed three profiles in a random sample—*slow and variable* ($n = 8$), *average* ($n = 24$), and *efficient* ($n = 20$)—that were marked by differences in children's development in arithmetic fact mastery from third grade to fifth grade. These profiles did not differ in terms of age, sex, socioeconomic status, or intellectual ability. In addition, we explored whether these profiles varied in cognitive skills that have been associated with individual differences in single-digit arithmetic. The three profiles differed in nonsymbolic and symbolic numerical magnitude processing as well as phonological processing, but not in digit naming or working memory. After also controlling for cluster differences in general mathematics achievement and reading ability, only differences in symbolic numerical magnitude processing remained significant. Taken together, our longitudinal data reveal that symbolic numerical magnitude processing represents an important variable that contributes to individual variability in children's acquisition of arithmetic facts.

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Introduction

Being skillful in single-digit arithmetic forms a major building block for future growth in more complex calculation skills (e.g., Kilpatrick, Swafford, & Findell, 2001). Previous studies have reported that there is large individual variability in the acquisition and use of arithmetic facts (e.g., Barrouillet, Mignon, & Thevenot, 2008; Dowker, 2005). The current longitudinal study investigated children's arithmetic fact development by applying, for the first time, a model-based clustering approach on different parameters of arithmetic fact mastery assessed at the start of three subsequent school years: third, fourth, and fifth grades. Different from a theory-driven top-down approach with a priori cutoff criteria to define subgroups, we employed a data-driven bottom-up approach to delineate clusters or profiles of arithmetic fact development by using model-based clustering (see Reeve, Reynolds, Humberstone, & Butterworth, 2012, for an example in the domain of numerical magnitude processing). This method also provides the opportunity to examine whether distinct profiles of arithmetic fact development also differ in terms of cognitive skills that have been associated with individual differences in single-digit arithmetic such as numerical magnitude processing, working memory, and phonological processing.

Arithmetic fact development

Numerous studies have described how children develop strategies to solve single-digit arithmetic (e.g., Bailey, Littlefield, & Geary, 2012; Siegler, 1996). Over time, children rely less on effortful and time-consuming procedural strategies, such as finger counting and decomposition, but they increasingly use direct and fast retrieval of arithmetic facts (e.g., Bailey et al., 2012; Barrouillet et al., 2008; Geary, 2013; Siegler, 1996). Jordan, Hanich, and Kaplan (2003) distinguished subgroups of arithmetic fact mastery based on children's performance on a forced arithmetic fact retrieval task at the end of third grade by using a priori determined cutoff criteria. The subgroup of children with poor arithmetic fact mastery (i.e., children with scores below the 25th percentile) showed little growth over time compared with children with good arithmetic fact mastery (i.e., scores between the 51st and 75th percentiles). These data suggested that difficulties in arithmetic fact mastery are highly persistent. One major issue in this study concerned the top-down categorization of children into subgroups based on predetermined cutoff criteria. It remained to be determined whether similar profiles can be identified when a data-driven bottom-up approach is used. The current study, therefore, aimed to investigate profiles of arithmetic fact development by means of cluster analysis and further examined whether these profiles differed in terms of cognitive skills that are known to contribute to individual differences in single-digit arithmetic, comprising numerical magnitude processing, working memory, and phonological processing. This allowed us to provide a more precise description of the cognitive characteristics of different profiles of arithmetic fact development in children.

Numerical magnitude processing

Various studies have linked proficient numerical magnitude processing skills, or people's elementary intuitions about quantity and their ability to understand the meaning of symbolic numbers (i.e., that they represent quantity), to individual differences in higher level mathematics achievement (see Chen & Li, 2014, and Fazio, Bailey, Thompson, & Siegler, 2014, for a meta-analysis; see De Smedt, Noël, Gilmore, & Ansari, 2013, for a narrative review). Two recently conducted meta-analyses revealed that children's nonsymbolic numerical magnitude processing skills were significantly associated with their mathematics achievement, although these associations were rather moderate (Chen & Li, 2014; Fazio et al., 2014). There is, however, some debate on associations between nonsymbolic numerical magnitude processing and mathematics achievement (see De Smedt et al., 2013, for a discussion) because some studies failed to find such (longitudinal) associations (e.g., Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012a; Vanbinst, Ghesquière, & De Smedt, 2012; see De Smedt et al., 2013, for a narrative review). In contrast, it has been argued that the results for symbolic numerical magnitude processing are more consistent (e.g., Bugden & Ansari, 2011; De Smedt,