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Developmental trajectories of children's symbolic numerical magnitude processing skills and associated cognitive competencies

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A B S T R A C T

Although symbolic numerical magnitude processing skills are key for learning arithmetic, their developmental trajectories remain unknown. Therefore, we delineated during the first 3 years of primary education (5–8 years of age) groups with distinguishable developmental trajectories of symbolic numerical magnitude processing skills using a model-based clustering approach. Three clusters were identified and were labeled as inaccurate, accurate but slow, and accurate and fast. The clusters did not differ in age, sex, socioeconomic status, or IQ. We also tested whether these clusters differed in domain-specific (nonsymbolic magnitude processing and digit identification) and domain-general (visuospatial short-term memory, verbal working memory, and processing speed) cognitive competencies that might contribute to children's ability to (efficiently) process the numerical meaning of Arabic numerical symbols. We observed minor differences between clusters in these cognitive competencies except for verbal working memory for which no differences were observed. Follow-up analyses further revealed that the above-mentioned cognitive competencies did not merely account for the cluster differences in children's development of symbolic numerical magnitude processing skills, suggesting that other factors account for these individual differences. On the other hand, the three trajectories of symbolic numerical magnitude processing revealed remarkable and stable

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differences in children's arithmetic fact retrieval, which stresses the importance of symbolic numerical magnitude processing for learning arithmetic.

Introduction

People are surrounded by Arabic numerical symbols, and numerical literacy has become a crucial skill for everyday life (e.g., Chiswick, Lee, & Miller, 2003; Gerardi, Goette, & Meier, 2013). Numerical literacy is a strong predictor of success at school (Duncan et al., 2007) and of future wealth (Basten, Jaekel, Johnson, Gilmore, & Wolke, 2015). It also has an impact on medical decision making in that it influences, for instance, people's perception of risks and benefits of screenings (Reyna, Nelson, Han, & Dieckmann, 2009). Over the past decade, researchers have investigated numerical literacy by estimating symbolic numerical magnitude processing skills, which reflect the ability to understand the numerical meaning of Arabic digits. Increasing evidence acknowledges the importance of these symbolic numerical magnitude processing skills for learning arithmetic (Dowker, 2005; Gilmore, Attridge, De Smedt, & Inglis, 2014; Jordan, Mulhern, & Wylie, 2009; Price & Fuchs, 2016; Siegler & Lortie-Forgues, 2014; Vanbinst, Ansari, Ghesquière, & De Smedt, 2016; see also De Smedt, Noël, Gilmore, & Ansari, 2013, for a narrative review, and Schneider et al., 2017, for a meta-analysis), but it remains unclear how children develop these symbolic skills.

The dominant view on the development of symbolic magnitude processing skills postulates that these skills are grounded in the ability to represent quantity in a nonsymbolic way (Bugden, DeWind, & Brannon, 2016; Merkley & Ansari, 2016; Siegler & Lortie-Forgues, 2014). Based on the evidence that human infants are able to discriminate between two sets of dots (nonsymbolic representations of quantity) (Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005), it has been assumed that children progressively learn the numerical meaning of Arabic numerical symbols by connecting these symbolic representations to nonsymbolic representations of quantity. Mundy and Gilmore (2009) specified that the period between 6 and 8 years of age is critical for scaffolding symbolic numerical magnitude representations onto nonsymbolic ones (see also Siegler & Lortie-Forgues, 2014). Studies showing associations between nonsymbolic numerical magnitude processing skills and children's concurrent and future (symbolic) mathematical competence (e.g., Halberda, Mazzocco, & Feigenson, 2008; Libertus, Feigenson, & Halberda, 2011, 2013; Starr, Libertus, & Brannon, 2013) indirectly confirm the connection between nonsymbolic and symbolic numerical magnitude processing. Against this background, nonsymbolic numerical magnitude processing skills are an important determinant of children's early acquisition of symbolic numerical magnitude processing skills (for a review, see Bugden et al., 2016; Merkley & Ansari, 2016; Piazza, 2010; Siegler & Lortie-Forgues, 2014).

Which other *domain-specific cognitive skills* might influence the acquisition of symbolic numerical magnitude processing skills? Clearly, to perform adequately on a symbolic comparison task, it is indispensable that children start with the correct and rapid identification of each presented Arabic numerical symbol (Merkley & Ansari, 2016). Only after identifying both digits can one compare the corresponding numerical quantities and decide on the larger one. Purpura, Baroody, and Lonigan (2013) recently showed that digit identification skills fully mediate the longitudinal association between preschool mathematical abilities of 3- to 5-year-olds and their future mathematical knowledge. The current study aimed to extend these findings by exploring whether individual differences in symbolic numerical magnitude processing might be explained by digit identification skills, which in turn might mediate the association between symbolic numerical magnitude processing and arithmetic. On the other hand, Reeve, Reynolds, Humberstone, and Butterworth (2012) investigated children's numerical development in dot enumeration and symbolic comparison and yet were not able to find associations between this numerical development and speed of identifying Arabic numerical symbols. The differences between these two studies might be explained by differences in age between