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Mathematical abilities in elementary school: Do they relate to number–space associations?

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ABSTRACT

Considering the importance of mathematics in Western societies, it is crucial to understand the cognitive processes involved in the acquisition of more complex mathematical skills. The current study, therefore, investigated how the quality of number–space mappings on the mental number line, as indexed by the parity SNARC (spatial–numerical association of response codes) effect, relates to mathematical performances in third- and fourth-grade elementary school children. Mathematical competencies were determined using the "Heidelberger Rechentest," a standardized German math test assessing both arithmetical and visuospatial math components. Stronger parity SNARC effects significantly related to better arithmetical but not visuospatial math abilities, albeit only in the relatively younger children. These findings highlight the importance of spatial–numerical interactions for arithmetical (as opposed to visuospatial) math skills at the fairly early stages of mathematical development. Differential relations might be explained by the reliance on problem-solving strategies involving number–space mappings only for arithmetic tasks mainly in younger children.

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Introduction

Considering the importance of mathematics in Western societies, it is crucial to understand its underlying cognitive mechanisms and early precursors. Building a thorough knowledge base of the different components of numerical thinking will not only help us to foster mathematical abilities in typically developing children but also enable the design of appropriate diagnostics and evidence-based interventions for children with mathematical learning difficulties. Basic numerical competencies, such as the comprehension and manipulation of quantity concepts and their associated symbols (i.e., number words and Arabic digits), are known to be foundational to more elaborate mathematical skills (Butterworth, 1999; De Smedt, Verschaffel, & Ghesquière, 2009; Dehaene, 1997). Over the past decade, much research has been dedicated to understanding how exactly these basic numerical skills relate to individual differences in performances on more advanced mathematical concepts and procedures (De Smedt, Noël, Gilmore, & Ansari, 2013; Hyde, Khanum, & Spelke, 2014; Libertus, Feigenson, & Halberda, 2011). Considering the crucial influence of especially symbolic numerical representations for later math achievement (Holloway & Ansari, 2009; Lyons & Beilock, 2011; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Sasanguie, Göbel, Moll, Smets, & Reynvoet, 2013; see also meta-analysis by Schneider et al., 2016), it seems particularly important to thoroughly understand and characterize the developmental trajectory of the comprehension of number symbols to gain better insights into the processes involved in the acquisition of more complex mathematical skills.

The representation of numerical quantities in general and number symbols in particular is intrinsically linked with spatial processes in typically developed human adults (Dehaene, Bossini, & Giraux, 1993; Dehaene, Dupoux, & Mehler, 1990; Fias, Lauwereyns, & Lammertyn, 2001; Fischer, 2001; Fischer, Castel, Dodd, & Pratt, 2003; Hoffmann, Mussolin, Martin, & Schiltz, 2014; Lammertyn, Fias, & Lauwereyns, 2002; Wood, Willmes, Nuerk, & Fischer, 2008; for a recent review, see Fischer & Shaki, 2014). A widely recognized concept for these spatial associations in numerical cognition is the mental number line (MNL; for reviews, see Dehaene, 1997; Hubbard, Piazza, Pinel, & Dehaene, 2005; Nieder, 2005), reflecting the idea that numerical quantities are represented along a horizontally oriented mental axis (Dehaene, 1992; Restle, 1970) that is universal across humans despite culturally mediated differences in its direction (mostly left-to-right orientation in Western cultures). According to the four-step developmental model of numerical cognition by von Aster and Shalev (2007), the process of Arabic symbolization constitutes a precondition for the formation of such a spatially oriented MNL. The fourth stage of numerical development is then assumed to be concluded with the establishment of spatial–numerical representations on the MNL at the beginning of primary school (von Aster & Shalev, 2007).

Inferences about the spatial representation of numerical quantities, and as such the disposition of the MNL, are usually derived from the external number line estimation task (e.g., Berteletti, Lucangeli, Piazza, Dehaene, & Zorzi, 2010; Booth & Siegler, 2006, 2008; Friso-van den Bos, Kolkman, Kroesbergen, & Leseman, 2014; Geary, Hoard, Nugent, & Byrd-Craven, 2008; Siegler & Opfer, 2003; for the original task, see Petitto, 1990). In this task, participants need to estimate the position of a given number on an empty number line labeled only with the start and end points (e.g., 0 and 100). Estimation performances are then considered as a direct and isomorphic measure of the MNL (e.g., Laski & Siegler, 2007; Opfer & Siegler, 2007; Siegler & Opfer, 2003). Performances on this task, therefore, are commonly studied in relation to mathematical abilities to determine the importance of spatial–numerical mappings on the MNL for math achievement.

Interestingly, the accuracy of number line estimations strongly relates to math achievement across different age groups (e.g., Booth & Siegler, 2006, 2008), thereby highlighting the potential importance of number–space mappings on the MNL for school-relevant mathematical competencies. Sasanguie et al. (2013), for instance, reported that children who were more accurate at placing symbolic digits on an external number line featured higher scores on a curriculum-based math task 1 year later. This was also confirmed by Schneider, Grabner, and Paetsch (2009), who reported that children's number line estimation performances were a reliable predictor of math achievement. In addition, children with math learning difficulties usually feature impaired performances on the number line estimation task (e.g., Geary, Hoard, Nugent, & Bailey, 2012; Geary et al., 2008; Landerl, 2013; von Aster & Shalev,