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Approximate number sense, symbolic number processing, or number–space mappings: What underlies mathematics achievement?

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In this study, the performance of typically developing 6- to 8-year-old children on an approximate number discrimination task, a symbolic comparison task, and a symbolic and nonsymbolic number line estimation task was examined. For the first time, children's performances on these basic cognitive number processing tasks were explicitly contrasted to investigate which of them is the best predictor of their future mathematical abilities. Math achievement was measured with a timed arithmetic test and with a general curriculum-based math test to address the additional question of whether the predictive association between the basic numerical abilities and mathematics achievement is dependent on which math test is used. Results revealed that performance on both mathematics achievement tests was best predicted by how well children compared digits. In addition, an association between performance on the symbolic number line estimation task and math achievement scores for the general curriculum-based math test measuring a broader spectrum of skills was found. Together, these results emphasize the importance of learning experiences with symbols for later math abilities.

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Introduction

In numerical cognition, there are two dominant approaches proposing different underlying factors leading to mathematical competence. First, domain-general approaches have proposed that variability in non-numerical skills such as phonological skills, working memory, long-term memory, and visuo-spatial processing underlies individual differences in mathematics achievement (e.g., Geary, 1993; Raghubar, Barnes, & Hecht, 2010). For instance, Passolunghi and Siegel (2004) observed a general working memory deficit in children with difficulties in mathematics. Alternatively, domain-specific approaches have proposed that individual differences in number-specific processes are related to variance in math skills (e.g., Dehaene, Piazza, Pinel, & Cohen, 2003; Piazza et al., 2010). Typically, domain-specific approaches assume an innate capacity for approximate number processing that is shared by human infants and other species (Agrillo, Piffer, Bisazza, & Butterworth, 2012; Cantlon, Platt, & Brannon, 2009). Studies on infants have provided evidence for this approximate number sense (ANS) (Xu & Spelke, 2000). The ANS has been suggested to form the basis of the arithmetic skill of 5-year-old children who had not yet been taught formal arithmetic but could compare, add, and subtract different dot arrays or sequences of sounds (Barth, Beckmann, & Spelke, 2008). Later, when children are confronted with symbols to represent numbers, these symbols are thought to acquire meaning by being associated with this preexisting nonsymbolic approximate representation (Mundy & Gilmore, 2009). Indeed, in tasks such as magnitude comparison, similar behavioral effects have been found with nonsymbolic and symbolic numbers (Cohen Kadosh, Lammertyn, & Izard, 2008). In the current study, we investigated three domain-specific numerical processes as possible predictors for individual differences in mathematics achievement: acuity of the ANS, performance in symbolic number comparison, and accuracy of number–space mappings of children.

In an ANS task, participants are instructed to decide which of two presented dot arrays contains the larger number of dots. Typically, ratio-dependent performance is observed following Weber–Fechner's law (Fechner, 1860); that is, participants are less accurate in discriminating two numerosities with a smaller ratio (e.g., ratio 1.25, 8 vs. 10 dots) than with a larger ratio (e.g., ratio 2, 8 vs. 16 dots). This ratio-dependent performance pattern can be expressed as a separate Weber fraction (w) for each participant. The Weber fraction reflects the minimum change in number that is needed for each participant to perceive a difference in number and, therefore, reflects the acuity of the ANS (Halberda, Mazzocco, & Feigenson, 2008; Piazza, 2010). This individual Weber fraction, as well as the mean accuracy on ANS tasks, has been shown to be related to children's performance on math achievement tests (e.g., Halberda & Feigenson, 2008; Inglis, Attridge, Batchelor, & Gilmore, 2011; Libertus, Feigenson, & Halberda, 2011; Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010). For instance, Inglis et al. (2011) showed that the Weber fraction measured with 7- to 9-year-olds is related to their performance on a math test. However, findings are inconsistent, and studies that did not find a relation between nonsymbolic number comparison and (future) mathematical abilities exist as well (e.g., De Smedt & Gilmore, 2011; Holloway & Ansari, 2009; Sasanguie, De Smedt, Defever, & Reynvoet, 2012; Soltész, Szücs, & Szücs, 2010).

Other authors have argued that it is not the representation of numerosities (as measured by discrimination performance) but rather the speed in accessing nonsymbolic magnitude representations from symbols that is crucial for predicting performance on math achievement tests (Rouselle & Noël, 2007). Evidence for this comes from findings with children with mathematical difficulties who perform worse on symbolic number comparison tasks than typically achieving children. In symbolic comparison tasks, the participants need to decide which is the larger number of a pair of single digits (1–9). This results in a distance effect; that is, reaction times are longer when two numerically close numbers (e.g., 8 vs. 9) need to be compared than when two numerically more distant numbers (e.g., 2 vs. 9) need to be compared. In developmental studies, the size of the distance effect decreases with age, and several studies have shown that either the size of the distance effect or average reaction times on symbolic comparison are related to individual differences in mathematics achievement. No such relationship has been reported for comparisons of dot patterns instead of digits (e.g., De Smedt & Gilmore, 2011; Holloway & Ansari, 2009; Landerl & Kölle, 2009; Lonnemann, Linkersdörfer, Heselhaus, Hasselhorn, & Lindberg, 2011; Sasanguie, De Smedt, et al., 2012). This seems to be at odds with studies

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