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Children's early understanding of number predicts their later problem-solving sophistication in addition

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ABSTRACT

Previous studies suggest that the sophistication of the strategies children use to solve arithmetic problems is related to a more basic understanding of number, but they have not examined the relation between number knowledge in preschool and strategy choices at school entry. Accordingly, the symbolic and nonsymbolic quantitative knowledge of 134 children (65 boys) was assessed at the beginning of preschool and in kindergarten, and the sophistication of the strategies they used to solve addition problems was assessed at the beginning of first grade. Using a combination of Bayes and standard regression models, we found that children's understanding of the cardinal value of number words at the beginning of preschool predicted the sophistication of their strategy choices 3 years later, controlling for other factors. The relation between children's early understanding of cardinality and their strategy choices was mediated by their symbolic and nonsymbolic quantitative knowledge in kindergarten. The results suggest that sophisticated strategy choices emerge from children's developing understanding of the relations among numbers, in keeping with the overlapping waves model.

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Introduction

Siegler's (1996) overlapping waves model provides the theoretical foundation for understanding individual differences in the strategies children use for problem solving and developmental change in their strategy mix. Children have multiple ways to solve most problems, and the strategy used to solve any given problem is based on procedural and associative memories formed during prior problem solving and a conceptual understanding of the domain (e.g., Shrager & Siegler, 1998; Siegler & Shrager, 1984). The brain systems underlying developmental change in children's strategy choices are now being studied (Qin et al., 2014), and the relation between strategy sophistication and concurrent and later academic achievement is well documented, especially for mathematics (Geary, Nicholas, Li, & Sun, 2017; Siegler, 1988). Despite the intensive study of children's strategy choices, little is known about the precursor knowledge that puts young children on the path to sophisticated problem solving. An especially important issue is the sophistication of the strategies they use to solve arithmetic problems at school entry because this is predictive of their growth in mathematical competencies throughout the elementary school years (Geary, 2011).

We addressed this knowledge gap with a 3-year longitudinal study of the relation between children's quantitative knowledge at the beginning of preschool and the sophistication of the strategies children used to solve addition problems in first grade, controlling for domain-general abilities (e.g., intelligence) and parental education. We begin with an overview of the mix of strategies that first graders use to solve addition problems and then describe the basic quantitative abilities that might provide the first steps toward sophisticated problem solving. The latter include children's basic knowledge of numerals and number words, as well as their intuitive understanding of nonsymbolic quantity, because these often predict later mathematics achievement (Desoete, Ceulemans, De Weerdt, & Pieters, 2012; Gilmore, McCarthy, & Spelke, 2007; Jordan, Kaplan, Locuniak, & Ramineni, 2007).

Children's strategy choices

First graders solve the majority of simple addition problems using four basic strategies (Baroody, 1984; Carpenter & Moser, 1984; Geary & Brown, 1991; Groen & Parkman, 1972; Siegler & Robinson, 1982; Siegler & Shrager, 1984). Children's initial problem solving is dominated by counting strategies (e.g., finger counting, verbal counting) that in turn are eventually replaced by more sophisticated retrieval-based strategies (e.g., decomposition, direct retrieval). Early on, children use their fingers to physically represent the addends and then count them to reach a sum. With verbal counting, children count audibly or move their lips as if counting implicitly. Whether counting fingers or counting verbally, children might count both addends starting from 1 (sum strategy), start with the smaller addend and count a number of times equal to the larger one (max strategy), or start with the larger addend and count a number of times equal to the smaller one (min strategy). The use of counting to solve these problems results in the formation of an associative relation between the problem and the generated answer.

The next time children see the same problem, memory representations of counting schema and the stored answer compete for expression. If the level of activation of the counting schema exceeds that of a candidate answer, then the counting procedure will be used. Repeated use of counting, however, builds the strength of the association between the problem and answer in long-term memory, and eventually results in use of retrieval-based problem solving (Siegler, 1996; Siegler & Shrager, 1984). One retrieval-based strategy involves decomposing the problem into more simple problems (Siegler, 1987). For example, the problem 5 + 7 might be solved by subtracting 2 from the 7, then retrieving the answer to 5 + 5, and finally adding back the 2. The use of decomposition is dependent on retrieval but also requires a conceptual understanding of number relations (Geary, Hoard, Byrd-Craven, & DeSoto, 2004). The other strategy is direct retrieval of the answer from long-term memory.