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Relations of different types of numerical magnitude representations to each other and to mathematics achievement

Lisa K. Fazio [a,*], Drew H. Bailey [a], Clarissa A. Thompson [b], Robert S. Siegler [a,c]

[a] Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213, USA
[b] Department of Psychology, University of Oklahoma, Norman, OK 73019, USA
[c] Siegler Center for Innovative Learning, Beijing Normal University, Beijing 100875, China

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ABSTRACT

We examined relations between symbolic and non-symbolic numerical magnitude representations, between whole number and fraction representations, and between these representations and overall mathematics achievement in fifth graders. Fraction and whole number symbolic and non-symbolic numerical magnitude understandings were measured using both magnitude comparison and number line estimation tasks. After controlling for non-mathematical cognitive proficiency, both symbolic and non-symbolic numerical magnitude understandings were uniquely related to mathematics achievement, but the relation was much stronger for symbolic numbers. A meta-analysis of 19 published studies indicated that relations between non-symbolic numerical magnitude knowledge and mathematics achievement are present but tend to be weak, especially beyond 6 years of age.

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Introduction

Precise representations of numerical magnitudes are foundational for learning mathematics. Both correlational and causal evidence link the precision of individual children's numerical magnitude

* Corresponding author.
E-mail address: lkf12@pitt.edu (L.K. Fazio).

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representations to their whole number and fraction arithmetic skill, memory for numbers, and other aspects of mathematical knowledge (Halberda, Mazzocco, & Feigenson, 2008; Holloway & Ansari, 2009; Siegler, Thompson, & Schneider, 2011; Thompson & Siegler, 2010). Such relations have been demonstrated with both symbolically expressed numbers (e.g., choosing the larger Arabic numeral) and non-symbolic numbers (e.g., choosing the more numerous dot array).

It remains unclear, however, how the symbolic and non-symbolic numerical magnitude representation systems are related to each other and whether each is uniquely related to mathematics achievement. It has been hypothesized that non-symbolic numerical magnitude representations give rise to symbolic ones and that both are related to mathematics achievement (e.g., Dehaene, 2011; Verguts & Fias, 2004), but experimental tests of these hypotheses have not yielded a consistent pattern. Nearly all of these experiments have used a single task (magnitude comparison), and all have used a single type of number (whole numbers); none has compared alternative models of the relations between the types of magnitudes and the relation of each to overall mathematics achievement. In addition, many studies have used narrow measures of mathematics achievement such as arithmetic performance rather than broad measures such as standardized mathematics achievement test scores.

In the current study, we seek to provide a broader and more general understanding of relations between symbolic and non-symbolic numerical magnitude representations and their unique relation to overall mathematics achievement. We pursue this goal by examining the relations of symbolic and non-symbolic numerical magnitude understanding on different tasks (magnitude comparison and number line estimation) and with different types of numbers (whole numbers and fractions) and then use these data to evaluate three models of relations among non-symbolic numerical magnitude representations, symbolic numerical magnitude representations, and mathematics achievement. We also try to explain the inconsistent relations between non-symbolic numerical magnitude knowledge and mathematics achievement by performing a meta-analysis that examines variables that might influence the relation between the two abilities.

Understanding of symbolic numerical magnitudes

Numerical magnitude understanding refers to the ability to comprehend, estimate, and compare the sizes of numbers (both symbolic and non-symbolic whole numbers and fractions). Numerical magnitude understanding is separate from other numerical abilities such as counting, cardinality, and arithmetic, and it deals solely with understanding numbers as magnitudes that can be compared and ordered. Such understanding is typically assessed using comparison or estimation tasks. Symbolic magnitude comparison tasks ask which of two Arabic numerals is larger (e.g., 3 or 6, 1/2 or 1/3). On such tasks, speed and accuracy increase with age, experience, and the distance between the numbers being compared (e.g., Moyer & Landauer, 1967; Sekuler & Mierkiewicz, 1977). Comparisons are faster and distance effects are smaller among students at selective universities than among community college students, suggesting a link between symbolic numerical magnitude understanding and mathematics proficiency even among adults (Schneider & Siegler, 2010). Moreover, symbolic magnitude comparison performance correlates positively with arithmetic skill and mathematics achievement test scores for comparisons of whole numbers (Castronovo & Gobel, 2012; De Smedt, Verschaffel, & Ghesquiere, 2009; Holloway & Ansari, 2009; Vanbinst, Ghesquiere, & De Smedt, 2012) and fractions (Hecht & Vagi, 2010; Siegler & Pyke, 2013; Siegler et al., 2011).

Another task that is often used to measure symbolic numerical magnitude understanding is number line estimation. Participants are shown a horizontal line with a number at each end and are asked to estimate other numbers' positions on the line. For example, if the line had 0 and 1000 at the two ends, 500 would go at the midpoint. As children gain experience with increasing ranges of numbers, their number line estimates become more accurate and more closely approximate a linear function (Siegler & Opfer, 2003). As with magnitude comparison, number line estimation accuracy for symbolically expressed whole numbers and fractions is closely related to both arithmetic proficiency and mathematics achievement (Ashcraft & Moore, 2012; Geary, 2011; Siegler & Booth, 2004; Siegler & Pyke, 2013; Siegler et al., 2011).

These two tasks, although superficially different, both tap children's understanding of numerical magnitudes. In each task, participants are asked to compare magnitudes: comparing the two

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