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The development of structural analogy in number-line estimation

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ABSTRACT

Recent studies have revealed that making number-line estimates requires not only number knowledge but also a host of other cognitive skills. Here, we argue that a fundamental component of number-line estimation is the act of relating the target number being estimated to another numerical reference point (e.g., a previous estimate, the endpoint of the line) and then extending this relation to the spatial domain—in other words, that children recruit analogical reasoning skills when estimating. Because such analogical comparisons require both the selection of a numerical reference point and the comparison of that reference point with the target number, we aimed to understand *which* reference points children use and *how* they use them. To this end, we tested whether and how 5-, 6-, and 7-year-olds used their previous estimates to constrain subsequent estimates. We found that children used their previous estimates as reference points, that older children used reference points differently than younger children, and that the ability to access previous estimates limited our youngest participants' ability to perform well on our number-line estimation task. We conclude that the analogical reasoning component of number-line estimation is substantial and shapes children's earliest estimation performance.

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Introduction

Number-line estimation—that is, the ability to place numbers on a physical line in correspondence to their relative magnitude—is often used to test theories of number knowledge, math skill, and cognitive development more broadly (Booth & Siegler, 2006; Ebersbach, Luwel, Frick, Onghena, & Verschaffel, 2008; Moeller, Pixner, Kaufmann, & Nuerk, 2009; Siegler & Booth, 2004; Siegler & Opfer, 2003; Siegler & Ramani, 2008). Estimation performance is predictive of math achievement (Booth & Siegler, 2008; Ramani & Siegler, 2008; Schneider, Grabner, & Paetsch, 2009; Siegler & Ramani, 2008) and memory for numbers (Thompson & Siegler, 2010), suggesting that the skills and knowledge measured by number-line estimation tasks are important to general academic success. Although most experiments on number-line estimation focus on how changes in estimation ability relate to the development of number knowledge, some recent studies have shown that number-line estimation depends not only on number knowledge but also on a cluster of additional capacities not directly related to number (Anobile, Stievano, & Burr, 2013; Barth & Paladino, 2011; Kolkman, Hoijtink, Koresbergen, & Leserman, 2013; Slusser, Santiago, & Barth, 2013). As a result, developmental changes in number-line estimation (and their correlation with other important cognitive factors) may stem in large part from changes to non-numerical capacities.

Many studies have found that children's ability to accurately place numbers on a number line improves gradually over development and that this improvement is characterized by a shift toward accurate linear estimation behavior within children's familiar number range (e.g., Booth & Siegler, 2006; Siegler & Opfer, 2003; Slusser et al., 2013). These changes to estimation performance depend, in part, on changes to children's understanding of the verbal number system. As children gain familiarity with a particular numerical range (e.g., 0–100), estimation improves in that range (but not necessarily for unfamiliar numbers, e.g., 101–1000). However, as noted above, improvements to estimation behavior might not indicate improvements to number knowledge alone; recent work has also related the development of number-line estimation ability to constructs as diverse as executive function and spatial proportion reasoning (Barth & Paladino, 2011; Kolkman et al., 2013; Slusser et al., 2013). These studies raise the possibility that improvements to estimation behavior arise not only from improvements to number knowledge but also from improvements to more domain-general cognitive skills. These studies also raise the more general point that estimation tasks might not just measure the accuracy of children's mental number line but may also measure other types of knowledge and skills.

In the current study, we explored the role of one such ability—analogical reasoning—in supporting number-line estimation. How might estimation ability require analogical reasoning skills? To understand the role of analogical reasoning in estimation performance, it is necessary to understand the processes involved in analogy and how these might apply to number-line estimation (for discussions, see Cantlon, Cordes, Libertus, & Brannon, 2009; Carey, 2009; Sullivan & Barner, 2012). Very generally, an analogy involves picking out a relation between entities in one domain and then applying this relation to entities in a separate domain. For example, consider the analogy that "a mitten is to a hand as a sock is to a foot" (or, in standard analogical notation, mitten:hand::sock:foot). This analogy involves two components. The first is a within-domain comparison (e.g., mitten:hand) that is used to extract the relation(s) between the entities in one domain (e.g., that a mitten goes on a hand, that mittens keep hands warm). The second is an across-domain comparison that applies the relation picked out by the within-domain comparison to entities in the new domain (e.g., that a sock goes on a foot, that socks keep feet warm).

Number-line estimation tasks involve precisely this kind of analogy. Because both the length of number lines and the range of values they represent can vary from one line to the next, the only way to construct an estimate is to relate the number being estimated to other numerically meaningful reference points. In other words, on any particular trial, the appropriate location for an estimate can be determined only by first comparing the number being estimated with other numerical reference points on the number line and by then translating the resulting numerical relation into an analogous spatial representation. For example, consider an estimate of 50 that is located 2 inches from the 0 point on a number line. Determining whether this estimate is accurate is impossible without knowing