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The emergence of "groupitizing" in children's numerical cognition

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ABSTRACT

Improvements in enumeration abilities that emerge over late childhood are primarily thought to reflect perceptual developments such as increases in subitizing limits for small sets and faster shifting of attention associated with serially counting larger sets. Contributions of conceptual knowledge development, such as the growing appreciation of how whole numbers are composed of subsets of whole numbers, are not as well understood. This study examined the emergence of a process referred to as "groupitizing," which captures how children may capitalize on grouping information to facilitate enumeration processes. We examined enumeration speed in a cross-sectional sample of children ($N = 378$), spanning kindergarten through third grade, using arrays of dots. Arrays were either unstructured or grouped by proximity into subsets in the subitizing range (i.e., three subgroups of 1–3 items). Kindergarten children showed no evidence of grouping structure on enumeration. First-grade children enumerated grouped arrays faster than unstructured arrays. This structure effect grew progressively stronger in subsequent grades. Enumeration speed for unstructured arrays increased with set size, yet for grouped arrays the impact of set size was dependent on grade level. For kindergartners, the grouping manipulation had no impact on the effect of set size. For older children, the grouping manipulation reduced the effect of set size on enumeration. Furthermore, individual differences in how set size affected enumeration of grouped arrays showed unique patterns of association with performance on standardized symbolic arithmetic fluency tests, suggesting a unique role for the

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construct of groupitizing in the development of enumeration fluency and symbolic math skills.

Introduction

The development of early proficiency in mathematics is foundational for academic achievement (McClelland, Acock, & Morrison, 2006; Parsons & Brynner, 2005) and an individual's economic prospects (Cawley, Conneely, Heckman, & Vytlacil, 1996). Interdisciplinary research across the fields of education and cognitive development has led to recent discoveries that variations in symbolic mathematical skills are linked to more fundamental aspects of numerical cognition. For example, individual differences in children's fluency with exact enumeration—the mental process of determining the exact number word that corresponds to the cardinal value of a set of items—are predictive of math skill development (e.g., Aunio & Niemivirta, 2010; Fischer, Gebhardt, & Hartnegg, 2008).

Interestingly, most psychophysical paradigms that study the development of cognitive processes of enumeration have focused on perceptual factors that govern enumeration speed such as how the number of items children can perceive in a single act of attention is linked to symbolic math skills (e.g., Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009). Such paradigms typically employ stimulus designs that systematically remove or minimize spatial grouping cues that may allow one to perceive subsets within each array. However, such designs likely minimize the potential contribution that conceptual developments in children's understanding of number may make to the development of enumeration fluency. For example, as children come to appreciate that an exact number is composed of many combinations of smaller numbers, they may capitalize on such conceptual developments during exact enumeration.

The current study aimed to investigate both perceptual and conceptual developments that may underlie the emergence of fluent enumeration and to examine how each of these developments contributes to individual differences in symbolic math skills. Our approach was to expand the typical enumeration fluency psychophysical paradigm by manipulating the presence or absence of spatial grouping cues. This provided an opportunity to measure the degree to which children take advantage of these grouping cues to overcome the perceptual limits that otherwise govern enumeration. This approach allowed us to experimentally dissociate perceptual components (i.e., limitations on how many items can be perceived at once) and conceptual components (i.e., knowledge of how small groups of items combine to form larger sets) of enumeration fluency. Furthermore, this design enabled a direct test of the hypothesis that cognitive mechanisms of exact enumeration, and their contribution to emerging fluency in symbolic arithmetic, undergo dramatic transformations over the early years of formal mathematics training.

Perceptual factors influence enumeration processes

In 1871, Stanley Jevons published one of the the first experimental studies on the limits of human perception in assessing exact enumeration. Using a clever "bean counting" paradigm, he demonstrated that he could enumerate quantities up through five beans nearly instantaneously, reflecting a single act of perception, yet beyond five enumeration accuracy decreased linearly with set size. This result suggested that despite having a concept of exactly 6, 7, and 8, one cannot directly access those representations via perception but rather must rely on an indirect process such as serial counting that requires an additional increment of time for each additional unit in a set. In the 140 years since this initial experiment was published, many studies have investigated the cognitive processes underlying the mental operation of exact enumeration, the distinctions between enumeration of small sets and larger sets, and how these processes emerge over the course of development (Beckwith & Restle, 1966; Chi & Klahr, 1975; Gallistel & Gelman, 1992; Kaufman, Lord, Reese, & Volkmann, 1949; Klahr, 1973; Logan & Zbrodoff, 2003; Piazza, Giacomini, Le Bihan, & Dehaene, 2003; Trick & Pylyshyn, 1994).