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Two core systems of numerical representation in infants

Yi Mou, Kristy vanMarle *

University of Missouri, Columbia, USA

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ABSTRACT

Two nonverbal representation systems, the analog magnitude system (AMS) and the object tracking system (OTS), have been proposed to explain how humans and nonhuman animals represent numerosities. There has long been debate about which of the two systems is responsible for representing small numerosities (<4). This review focuses on findings with human infants to inform that debate. We argue that the empirical data cannot all be explained by a single system, and in particular, infants' failures to compare small and large numerosities – the *boundary effect* – undermines the claim that the AMS can account for infants' numerical abilities in their entirety. We propose that although the two systems coexist throughout the lifespan, competition between the systems is primarily a developmental phenomenon. Potential factors that drive the engagement of each system in infancy, such as stimulus features and task demands, are discussed, and directions for future research are suggested.

Introduction

"What does a fish know about the water in which it swims all its life?" (Einstein, 1950, p. 5). What do we know about the world full of numerical information in which we live all our lives? What is the nature of our numerical concepts and where do they come from? Four lines of research have contributed to our understanding of these important issues. Comparative psychology has shown that basic numerical concepts are not unique to humans but shared across many animal species, and thus an abstract concept of number is not dependent upon language. Comparative studies also point to the

* Corresponding author. Address: Department of Psychological Sciences, University of Missouri, 210 McAlester Hall, Columbia, MO 65211, USA. Fax: +1 (573) 882 7710.

E-mail address: vanmarlek@missouri.edu (K. vanMarle).

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evolutionary roots of human numerical knowledge and how numerical abilities are critical for organisms' survival (Cantlon, 2012; Dehaene, 1997; Gallistel, 1990; Gallistel & Gelman, 2000; Vallortigara, Chiandetti, Rugani, Sovrano, & Regolin, 2010). Developmental psychology has demonstrated that even preverbal human infants possess abstract numerical concepts and show quite sophisticated numerical abilities. Before age one, infants discriminate, order, and perform arithmetic operations over nonverbal numerical representations (Brannon & Roitman, 2003; Carey, 2009; Gallistel & Gelman, 2000; Piazza, 2010), and the basis for these capacities is present even in newborns (Izard, Sann, Spelke, & Streri, 2009). Such research examines the origins of human numerical concepts and investigates how the concepts change with age, experience and education. Cross-cultural research examines the similarities and differences in humans' numerical abilities within different cultures and emphasizes how cultures may shape and influence these concepts (e.g., Dehaene, 1997). Finally, cognitive neuroscience investigating both normal and brain-injured individuals reveals the physiological basis of these numerical concepts and abilities (e.g., Piazza, 2010). Taken together, the findings from these four areas of research suggest that abstract numerical concepts exist across species, across cultures, and throughout development. Indeed, numerical knowledge is considered one of only a handful of core knowledge domains that may be innate and which plays a fundamental role in the cognition of humans (Carey, 2009; Feigenson, Dehaene, & Spelke, 2004; Spelke, 2000, 2004; Spelke & Kinzler, 2007), and many nonhuman species (Rugani, Vallortigara, & Regolin, 2013; Vallortigara et al., 2010).

Debate continues over the format of nonverbal number representations. Nonetheless, converging evidence from the four research approaches suggests that humans and nonhuman animals share a mechanism that represents both discrete and continuous quantities (e.g., duration and spatial quantities) as fuzzy mental magnitudes (e.g., Beran, Decker, Schwartz, & Schultz, 2011; Brannon & Merritt, 2011; Brannon & Roitman, 2003; Carey, 2009; Dehaene, 1997; Feigenson et al., 2004; Gallistel & Gelman, 2000, 2005; Gibbon, 1977; Meck & Church, 1983; Spelke & Kinzler, 2007). Due to the noisy nature of the analog magnitude system (AMS), the discrimination of two quantities is determined by their ratio, in accord with Weber's law. Despite the wealth of evidence for the AMS, researchers have asked whether humans and nonhuman animals might use a distinct mechanism to represent small numbers ($\leqslant 4$).

The idea that small numbers may be represented differently from large numbers is not new (e.g., Jevons, 1871; Taves, 1941; Warren, 1897). More than six decades ago, Kaufman, Lord, Reese, and Volkmann (1949) showed that adults were fast and accurate when estimating small sets of items (up to about 6), but that estimation for larger sets was error prone and slow, with reaction time (RT) increasing linearly with each additional item for large sets, while it remained relatively constant for sets of 1–6 items. Kaufman et al. concluded that the different slopes for reaction time and accuracy across the small and large number ranges indicated that adults were using distinct processes and coined the term "subitizing" to describe the process used for small sets. More recent studies exploring the two-system hypothesis have proposed that a mechanism of visual attention – the object tracking system (OTS) – may account for adults' fast and accurate performance with small sets (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008; Trick, 2008; Trick, Audet, & Dales, 2003; Trick, Enns, & Brodeur, 1996; Trick & Pylyshyn, 1994). In contrast to the AMS, the signature property of the OTS is its limited capacity (cf. Alvarez & Cavanagh, 2004 and Alvarez & Franconeri, 2007). Instead of representing the overall magnitude of a set (i.e., cardinality), it simultaneously indexes each individual object in an array up to its capacity limit of about 3 or 4 items (Feigenson & Carey, 2003, 2005; Feigenson, Carey, & Hauser, 2002; Pylyshyn & Storm, 1988; Scholl, 2001; vanMarle, 2013). For this system, two sets are discriminable (via a one-to-one correspondence operation) as long as they are both within the capacity limit, regardless of their ratio (e.g., 3v4 is no more difficult than 1v2).

There continues to be substantial debate about the two-system view (Feigenson et al., 2004; Gallistel & Gelman, 2000, 2005; Hyde, 2011; Piazza, 2010; Trick & Pylyshyn, 1994). On one side, researchers argue that a single mechanism, the AMS, suffices for processing numbers throughout the number range, and therefore it is not necessary to posit the engagement of another mechanism (e.g., Beran, 2007; Cordes & Brannon, 2009; Cordes, Gelman, Gallistel, & Whalen, 2001; Gallistel & Gelman, 2000, 2005). Another view is that the two systems are distinct and mutually exclusive, with the OTS limited to representing small numbers and the AMS limited to representing large numbers (Feigenson, Carey, & Hauser, 2002; Piazza, 2010; Xu, 2003). Yet a third view, and the stance taken here,