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Open questions and a proposal: A critical review of the evidence on infant numerical abilities

Lisa Cantrell *, Linda B. Smith

Indiana University, Bloomington, IN, United States

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ABSTRACT

Considerable research has investigated infants' numerical capacities. Studies in this domain have used procedures of habituation, head turn, violation of expectation, reaching, and crawling to ask what quantities infants discriminate and represent visually, auditorily as well as intermodally. The concensus view from these studies is that infants possess a numerical system that is amodal and applicable to the quantification of any kind of entity and that this system is fundamentally separate from other systems that represent continuous magnitude. Although there is much evidence consistent with this view, there are also inconsistencies in the data. This paper provides a broad review of what we know, including the evidence suggesting systematic early knowledge as well as the peculiarities and gaps in the empirical findings with respect to the concensus view. We argue, from these inconsistencies, that the concensus view cannot be entirely correct. In light of the evidence, we propose a new hypothesis, the Signal Clarity hypothesis, that posits a developmental role for dimensions of continuous quantity within the discrete quantity system and calls for a broader research agenda that considers the covariation of discrete and continuous quantities not simply as a problem for experimental control but as information that developing infants may use to build more precise and robust representations of number.

1. Introduction

Considerable research suggests that numerical reasoning originates in a basic capacity that is independent of culture or language. When asked to discriminate, estimate, or transform quantities, human adult judgments are systematic without the use of counting or formal mathematical strategies. For small quantities, humans have shown exact judgments within the range of 1 to approximately 4 items (Kafman, Lord, Reese, & Volkmann, 1949; Mandler & Shebo, 1982; Taves, 1941). Large quantity judgments, although not exact, are systematically patterned across species: for human and nonhuman primates—as well as a large range of other animals including rats and pigeons—discrimination is subject to Weber's Law (Brannon & Terrace, 1998; Cordes, Gelman, Gallistel, & Whalen, 2001; Meck & Church, 1983; Roberts & Mitchell, 1994; Whalen, Gallistel, & Gelman, 1999). In the past three decades research has pursued the question of whether human infant numerical judgments show these same signature regularities. The consensus is that they do (Carey, 2009; Dehaene, 1997; Feigenson, Dehaene, & Spelke, 2004); results from experiments using a variety of different methods show that infants discriminate, track, and transform quantities and do so in ways that resemble the behavioral patterns of adults and other animals in laboratory experiments (e.g., Cordes & Brannon, 2009b; Xu & Spelke, 2000; Xu, Spelke, & Goddard, 2005).

Accordingly, the predominant view—and the starting point for many theories of numerical concepts—is that human infants have a capacity to represent discrete amounts (e.g., Carey, 2009; Cordes & Brannon, 2008; Feigenson et al., 2004; Spelke & Kinzer, 2007; Xu & Spelke, 2000). By this perspective, infants perceive, represent, and

* Corresponding author. Address: Department of Psychological and Brain Sciences, Indiana University, Bloomington, IN, United States. Tel.: +1 812 855 8256.

E-mail address: cantrell@indiana.edu (L. Cantrell).

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discriminate quantities using an evolutionarily ancient system – one that is specifically tuned to number. There is substantial evidence for this general conclusion. However, there are two additional theoretical ideas associated with this proposal. The first of these is that the evolutionarily ancient numerical system is fundamentally separate from other systems of magnitude discrimination and representation. The second is that the discrete number system is abstract and amodal, and thus not limited to one sensory modality but rather applicable to the quantification of *any* kind of entity (e.g., sights, sounds, actions, Lipton & Spelke, 2003, 2004; Wynn, 1996). An abstract and early discrete number system that is distinct from other forms of magnitude judgment is counter to the classic developmental theory of Piaget (1952), which proposes that the capacities observed in infancy—although the foundation of later numerical competence—are not initially specific to number. There are also contemporary researchers who suggest that a discrete number system may be built out of a more general magnitude system (see Gebuis & Reynvoet, 2011; Mix, Huttenlocher, & Levine, 2002; see also Lourenco & Longo, 2011 for related perspectives); but this is the minority view in the literature.

The claim that infant or adult perception of discrete quantity is in some way *separate* from the modality specific properties of the array including other dimensions of magnitude (such as the amount of visual spread in an array) is difficult to demonstrate empirically and is the source of complication for experimental methods. These complications are especially problematic in the infant literature given the necessary limits on the number of trial types and dependent measures. The fundamental problem is that discrete quantity in the environment is correlated with other stimulus dimensions; as the number of discrete elements in a set increases, other perceptual properties change as well, and although one might control one of these properties in any one experiment, all of them cannot be controlled simultaneously. These complexities in experimental control bring us to the core question motivating this review: The consensus view of an evolutionarily old, mechanistically distinct and developmentally early number system yields a set of clear predictions. Although many of these predictions are supported by empirical data, there are also key failures. How should the field understand these problematic results and how should we evaluate the consensus view in their light?

To address these questions, we first provide a comprehensive review of studies that investigate quantitative capacities in infants—many of which support the consensus view. We then take a closer look at the more problematic cases. Our conclusion is that the acceptance of the predominant view is not yet warranted and that these problematic cases might not be best viewed as noise that can be ignored but rather as the nonsinging canary in the coal mine—an indication that there is something amiss in our current understanding of early quantitative capacities. In the final section we propose a new theoretical framework that may more wholly account for the data: infants are highly sensitive to the statistical regularities in the environment; there are correlations between discrete quantity and other dimensions of magnitude, and these correlations support the development of internally-stable and finely-tuned quantity judgements. Our proposal is compatible with the idea of an evolutionarily and developmentally early number system, although it might require a modification in our conception of exactly *what* the evolutionarily early system *is* and may require us to abandon the assumption that the numerical system is completely segregated from other dimensions of continuous quantity representation or abstract at its onset. Whether our proposal or the current concensus view proves more correct in the end, our analysis also suggests the value of a shift in the research agenda—a shift away from the current emphases that rule out a role for stimulus properties other than number itself to a study of numerical cognition—and a study of the developmental changes in how nonsymbolic number is processed—that is in relation to the correlated dimensions of magnitude.

2. Current research in infants' numerical capacities: methods and findings

2.1. Infants' numerical discriminations: detecting differences visually and auditorily

The first studies of infant numerical abilities and many that have followed in the past three decades have tested discrimination of nonsymbolic quantities using habituation and familiarization procedures. The studies have asked the empirical question of whether infants can tell the difference among varying numerosities of geometric figures, pictures, events, or sounds. In a seminal study, Starkey and Cooper (1980) habituated 3–22 week old infants to visual displays of various numerosities (e.g., 2 or 3 black dots) and then presented the infants novel quantities. In testing, infants dishabituated to a change in number; infants habituated to 2 dots dishabituated to 3 and vice versa, indicating that they detected the change in quantities. Studies that followed found similar results. Antell and Keating (1983) found the same result in a replication of this experiment with neonates. In another classic study, Strauss and Curtis (1981) habituated infants to arrays of pictures of everyday items that varied in their quantities. In this experiment, 10–12 month old infants also discriminated 2 from 3 items as well as 3 from 4.

Since the original Starkey and Cooper (1980) study, many other experiments have used this same general procedure to investigate infants' abilities. A list of visual numerical discrimination studies using the habituation or familiarization procedure is found in Table 1. The studies in the table are organized according to the quantities tested and are arranged in the general ascending order of those quantities with columns indicating whether infants discriminated the quantities. The accumulation of data, as can be seen in Table 1, has formed a picture of a capacity with signature traits. One signature trait is the ratio limit of large number discrimination; infants discriminate large quantities only approximately rather than based on absolute values, detecting differences in accordance with Weber's Law. For example, infants at 6 months discriminate differences at a 1:2 ratio; they discriminate 8 from 16