Beyond number: Towards a unified view of dimensional reasoning in perception, cognition, and language

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Introduction

Natural number concepts play a fundamental role in abstract human thought, being central to mathematics, science and measurement, as well as pervasive in our everyday reasoning. A major turning point in our understanding of the psychological bases of number came with the discovery of an approximate, analog system for representing numerical magnitude found to underlie our numerical intuitions in tasks ranging from relative numerosity judgments, to addition, subtraction, and ordering, among others. Crucially, such analog magnitude representations are involved not just for number, but for all other kinds of dimensions as well, from *physical size*, *loudness, brightness*, and *duration* (e.g. Fias et al. 2003; Cordes & Brannon, 2008), to more evaluative dimensions like *likelihood* (Wellman, Kushnir, Xu & Brink, 2016). Based on extensive studies on human adults, children, pre-verbal infants and non-human species, we now understand the systems underlying the mental representation of scalar dimensions to be best characterized as approximate, analog representations with signature ratio limits (obeying Weber's Law), operational in humans from birth and throughout the lifespan, and shared with a wide range of other animal species.

The primary goal of this symposium is to bring recent developments from infant and comparative psychological research pertaining to our understanding of analog magnitude systems to a broader audience of cognitive scientists, to discuss their implications for human cognition. With a more complete picture of the kinds of inferential capacities afforded by analog magnitude and other systems in non-human animals and preverbal infants, we are in a better position to understand the interplay between language and non-linguistic systems in the human mind.

Recent developments

A wealth of research in developmental and comparative cognition in recent years has revealed previously unexpected inferential capacities in infants and non-human animals that are evidently supported by analog magnitude representations.

Cross-dimensional mapping in infancy

It is well-known that adults and children readily map analog magnitude representations to one another (e.g. Stevens & Marks, 1965), but it is a more recent discovery that this tendency in fact begins in infancy. For example, given evidence for a correspondence between numerosity and line length in a visual habituation task, human newborns expect shorter lines to correspond to smaller numerosities, and longer lines to correspond to larger numbers (de Hevia & Spelke, 2010). That newborn infants spontaneously map between number and space, as well as duration (de Hevia et al., 2014), suggests that at least some kinds of scalar mappings may precede experience. Importantly, older infants have been shown to learn more arbitrary mappings in a context-specific manner as well (Lourenco & Longo, 2010), raising the possibility that tracking correspondences between environmentally co-occurring variables may be one way in which infants learn about their physical (and social) worlds in infancy, before access to language.

Transitive inference in animals

Yet another reasoning strategy implicated to be subserved by the analog magnitude systems is transitive inference (TI), the ability to infer from $A > B$ and $B > C$ that $A > C$. Extensive and well-controlled studies of non-human animals in recent decades have revealed a pervasive capacity for transitive inference in species ranging from fellow primates and mammals, to birds, amphibians, and fish. The capacity to represent ordinal relationships is a prerequisite for transitive inference, and as such, TI can be considered a kind of order-based reasoning. Cantlon and Brannon (2006) find behavioural evidence for shared systems for ordering numerical magnitudes in humans and monkeys, and moreover that both groups exhibit semantic congruity effects, signalling a common mental comparison process (Cantlon & Brannon, 2005). The preponderance of evidence for successful non-symbolic TI and order-sensitivity in the animal literature has important implications for human reasoning that are yet to be fully explored by the cognitive scientific community. Such evidence should be of particular interest to those investigating the conceptual foundations of symbolic thought, given the implication that the binary *more than* relation ('<') in language and mathematics may have its basis in analog magnitude systems.

Scalar phenomena in language

In linguistics, conceptual and pragmatic scales are invoked in explanations of linguistic phenomena ranging from gradable adjectives ('*tall*', '*fast*', '*large*', '*ambitious*') and comparative and superlative constructions ('*Ben is taller*

than Dan'; '*Ben is the tallest*'), to scalar implicature (Horn 1972; Hirschberg 1985), to name a few. That classic behavioral signatures of analog magnitude systems --- the symbolic distance effect (e.g. Moyer & Landauer, 1967) and semantic congruity effects (e.g. Banks, Clark & Lucy, 1975) --- arise in tasks involving gradable adjectives, provides some support for links between these linguistic labels and underlying analog format representations. But most well-studied in this regard are the bidirectional linkages between natural numbers (<'*one*', '*two*', '*three*', …>), and corresponding analog magnitude representations in the numerate human mind (Odic, Le Corre & Halberda, 2015). Given that both the number scale as well as scales comprised of gradable adjectives give rise to scalar implicatures, it is worthwhile to consider whether similar mechanisms to those supporting dimensional inference in infants and animals, may also be involved in scale-based reasoning in humans. As it happens, there is recent evidence for the use of parallel strategies for scalar inference by children and adults in non-linguistic tasks (Kampa & Papafragou, 2019; Gweon & Asaba, 2018) lending credence to this possibility.

The pervasiveness of scalar phenomena cross-linguistically, in light of the developments highlighted above, raises the following questions: First, taking for granted that conceptual scales are indeed psychologically 'real', how should they be characterized in psychological terms? What is the precise nature of the relationship between conceptual and/or pragmatic scales, and associated analog magnitude representations? Finally, are there deeper connections between the inferential capacities afforded by analog magnitude systems in preverbal infants and nonverbal animals, and the widely-studied phenomena of scalar and quantity-based inference in linguistically-savvy humans? More specifically, might there be shared neural and cognitive mechanisms for the computation of dimensional inferences in the linguistic, cognitive, and perceptual domains?

Linguists in the 1980's and 90's theorized the existence of 'scalar models' that map between two or more correlated dimensions to support implicit inferences arising with scalar language (e.g. Fauconnier, 1975; Kay, 1990; Israel 1996). Although such cognitive accounts subsequently fell out of favor within mainstream linguistic theory, the empirical clarity provided by psycholinguistic findings in recent years has convinced some that a better understanding of the conceptual structures that language links up to "under the hood" may be essential to account for the distribution of various classes of linguistic inference (Paul, 2018). The superficial similarity of the early theoretical models of scalar linguistic reasoning to the recent empirical results from the infant literature (i.e., bidirectional mappings between statistically correlated properties), suggests the former may be ripe for revisiting. The different disciplines studying phenomena involving the representation of dimensional attributes stand to gain from sharing insights across disciplinary boundaries, something we hope to foster with this symposium. Moreover, this symposium has the potential to inspire renewed efforts towards a more psychologically informed model of scalar reasoning in language, and possibly even a unified model of dimensional reasoning in human and animal cognition.

Speakers:

Stella Lourenco will represent the perspective from infant cognition, specifically her research on cross-dimensional mappings in infancy, as well as some brand new cognitive neuroscientific results from her lab supporting a generalized system of magnitude representation.

Jessica Cantlon will discuss the comparative cognitive perspective, including findings of parallel behavioral patterns in human adults and monkeys in numerical ordering and other tasks, and what this reveals about our shared mental processes for magnitude comparison.

Anna Papafragou will focus on the development of scalar implicature, and present new work showing that adults and children's behavioral patterns in non-linguistic and linguistic versions of a task eliciting scalar implicature are guided by a common principle.

Pooja Paul will employ her background in linguistics and developmental psychology to disentangle the contributions of extra-linguistic domains from that of language in scalar reasoning. Her presentation will synthesize the different strands of research presented during the symposium, and paint a picture of what a unified theory of dimensional reasoning might look like.

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