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The discovery and comparison of symbolic magnitudes

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ABSTRACT

Humans and other primates are able to make relative magnitude comparisons, both with perceptual stimuli and with symbolic inputs that convey magnitude information. Although numerous models of magnitude comparison have been proposed, the basic question of how symbolic magnitudes (e.g., size or intelligence of animals) are derived and represented in memory has received little attention. We argue that symbolic magnitudes often will not correspond directly to elementary features of individual concepts. Rather, magnitudes may be formed in working memory based on computations over more basic features stored in long-term memory. We present a model of how magnitudes can be acquired and compared based on BARTlet, a representationally simpler version of *Bayesian Analogy with Relational Transformations* (BART; Lu, Chen, & Holyoak, 2012). BARTlet operates on distributions of magnitude variables created by applying dimension-specific weights (learned with the aid of empirical priors derived from pre-categorical comparisons) to more primitive features of objects. The resulting magnitude distributions, formed and maintained in working memory, are sensitive to contextual influences such as the range of stimuli and polarity of the question. By incorporating psychological reference points that control the precision of magnitudes in working memory and applying the tools of signal detection theory, BARTlet is able to account for a wide range of empirical phenomena involving magnitude comparisons, including the symbolic distance effect and the semantic congruity effect. We discuss the role of reference points in cognitive and social decision-making, and implications for the evolution of relational representations.

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1. Introduction

Humans and other primates have sophisticated abilities to learn and make judgments based on relative magnitude. Magnitude comparisons are critical in making choices (e.g., which of two products is more desirable?), making social evaluations (e.g., which person is friendlier?), and in many other forms of appraisal (e.g., who can run faster, this bear or me?). In addition to making comparisons based on elementary perceptual dimensions (e.g., identifying the longer of two line segments or the brighter of two lights), people are able to make analogous judgments based on symbolic dimensions using information stored in memory (e.g., the relative size or intelligence of various animals). Non-human primates are also capable of at least rudimentary symbolic comparisons. For example, rhesus monkeys are capable of learning shapes (Arabic numerals) that correspond to small numerosities (1–4 dots), such that the shapes acquire neural representations overlapping those of the corresponding perceptual numerosities and can be compared on that basis (Diester & Nieder, 2007).

Striking parallels have been observed between perceptual and symbolic judgments. In particular, both perceptual and symbolic judgments yield a *distance* effect, such that the ease of judgments (indexed by accuracy and/or reaction time) increases with the magnitude difference between the objects being compared (e.g., Moyer, 1973; Moyer & Bayer, 1976; Moyer & Landauer, 1967). A symbolic distance effect is observed not only with quasi-perceptual dimensions such as size, but also with more abstract dimensions such as animal intelligence (Banks, White, Sturgill, & Mermelstein, 1983) and with scalar adjectives of quality (e.g., *good*, *fair*; Holyoak & Walker, 1976). Non-human primates also exhibit a distance effect for judgments along various perceptual dimensions, including numerosity (Nieder & Miller, 2003).

When judgments are made using contrastive polar concepts (e.g., "choose brighter" versus "choose dimmer", "choose better" versus "choose worse"), both perceptual (Audley & Wallis, 1964; Petrusic & Baranski, 1989; Wallis & Audley, 1964) and symbolic judgments also yield a *semantic congruity* effect: for objects with high values on the dimension, it is easier to judge which object is greater, whereas for objects with low values, it is relatively easier to judge which is lesser (e.g., Banks, Clark, & Lucy, 1975; see Moyer & Dumais, 1978, for an early review). Like the distance effect, semantic congruity effects have also been obtained with monkeys (Cantlon & Brannon, 2005). A further phenomenon, the *markedness* effect, refers to the fact that for some pairs of polar adjectives, one (the "unmarked" form) is easier to process overall than the other (Clark, 1969). For example, the "unmarked" question "Which is larger?" tends to be answered more rapidly overall than the "marked" question "Which is smaller?" (Clark, 1969; Clark, Carpenter, & Just, 1973). The impact of markedness implies that the congruity effect often takes the form of an asymmetrical interaction.

1.1. How are magnitudes generated?

Numerous models of symbolic magnitude comparisons have been proposed, and we will review several of them below. However, in the present paper we focus on a question that (even though it is arguably the most basic of all) has seldom been asked, far less answered: where do subjective magnitudes come from? In the case of perceptual judgments with unidimensional stimuli (e.g., tones varying in loudness), it is reasonable to assume that a specific neural channel generates magnitudes. For symbolic comparisons, the tacit assumption has been that the long-term memory representation of each object being compared includes a magnitude value (perhaps with an associated variance), and that these magnitudes are simply retrieved and loaded into working memory, where a comparison process operates.

For a few types of symbolic comparisons, such as numerical magnitudes of digits, it may indeed be the case that each object has a pre-stored magnitude in long-term memory. But for more complex dimensions this assumption is questionable, and indeed quite unrealistic. Even symbolic size judgments, which are closely linked to perceptual features, are unlikely to always be based on pre-stored magnitudes, as size is actually a complex function of three-dimensional shape. Indeed, recent evidence indicates that although numerical magnitudes are automatically activated when reading integers, size