Cognition 169 (2017) 36–45

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

Spontaneous, modality-general abstraction of a ratio scale

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ARTICLE INFO

Article history:
Received 25 September 2016
Revised 26 July 2017
Accepted 29 July 2017
Available online 12 August 2017

Keywords:
Generalized magnitude representation
Ratio scale

ABSTRACT

The existence of a generalized magnitude system in the human mind and brain has been studied extensively but remains elusive because it has not been clearly defined. Here we show that one possibility is the representation of relative magnitudes via ratio calculations: ratios are a naturally dimensionless or abstract quantity that could qualify as a common currency for magnitudes measured on vastly different psychophysical scales and in different sensory modalities like size, number, duration, and loudness. In a series of demonstrations based on comparisons of item sequences, we demonstrate that subjects spontaneously use knowledge of inter-item ratios within and across sensory modalities and across magnitude domains to rate sequences as more or less similar on a sliding scale. Moreover, they rate ratio-preserved sequences as more similar to each other than sequences in which only ordinal relations are preserved, indicating that subjects are aware of differences in levels of relative-magnitude information preservation. The ubiquity of this ability across many different magnitude pairs, even those sharing no sensory information, suggests a highly general code that could qualify as a candidate for a generalized magnitude representation.

1. Introduction

Magnitudes such as size, duration, and number share similar psychophysical signatures, appear to use overlapping neural resources, and can influence each other in dual tasks. These observations are consistent with the existence of a shared analog code or generalized magnitude representation (Gallistel & Gelman, 2000; Holyoak & Glass, 1978; Pinel, Piazza, Le Bihan, & Dehaene, 2004; Walsh, 2003; see Bonn & Cantlon, 2012; Bueti & Walsh, 2009; Cantlon, Platt, & Brannon, 2009; Cohen Kadosh, Lammertyn, & Izard, 2008; and Lourenco, 2015 for extensive reviews). However, the shared-code hypothesis remains underspecified because the existing data has not revealed much about the code's internal structure. In addition, it remains unclear whether the many studies demonstrating interactions between magnitude dimensions are tapping into more than one possible mechanism.

At a minimum, a shared code should be inherently meaningful across many magnitude domains and across sensory modalities. Two types of relative-magnitude representation—ratios and ranks—automatically offer such generality at different levels of granularity. Ratios and ranks are dimensionless quantities that abstract away from original metrics; for example, the ratio of 1:2 is meaningful on any intensity scale such as loudness or size. Some recent evidence suggests that ratios, represented by pairs of lines of different length or subsets of dot arrays painted in a particular color, are spontaneously represented in a fronto-parietal network in adult humans and macaques (Vallentin & Nieder, 2008, 2010; Jacob & Nieder, 2009; Jacob, Vallentin, & Nieder, 2012), but it is unclear whether these representations are restricted to their particular dimensions. In principle, ratios could support cross-dimension mapping between pairs of structurally similar analog magnitudes (Srinivasan & Carey, 2010), but current evidence for such transfer is limited.

We explore the possibility that humans spontaneously represent fine-grained information about ratios and ranks in a format that can be compared across modalities and dimensions, providing a candidate for a generalized magnitude representation.

1.1. Current evidence for cross-dimension transfer of relative magnitudes

An abstract representation of relative magnitude should allow observers to transfer information about a set of two or more stimuli from one dimension to another without presenting both dimensions simultaneously. Evidence for the transfer of representations of relative magnitude across dimensions or across sensory

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http://dx.doi.org/10.1016/j.cognition.2017.07.012
0010-0277/

modalities is scattered across several literatures; here we review a selection of representative examples.

Magnitude-estimation experiments designed to measure subjective sensation demonstrated that after observing a change in magnitude in one dimension relative to an anchor stimulus, subjects are able to generate equivalent proportional changes in other dimensions, given explicit instruction (Luce, 1990, 2002; Shepard, 1981; Stevens, 1975; Stevens, Mack, & Stevens, 1960). However, more ambiguous instructions in this task could elicit a wider range of magnitude estimates from unconstrained, heterogeneous transformation rules. Using a more constrained bisection task, Balci and Gallistel (2006) found that within-dimension calculation of proportions likely explained the transfer of duration discrimination to numerical discrimination behavior in humans, but it is unknown how generalizable this result is across multiple dimensions, and whether subjects spontaneously represent rank or proportion relations from sequences.

Cross-dimension transfer of relative magnitudes has been shown in infants for more imprecise representations resembling the concepts of *more* or *less*. For example, Lourenco and Longo (2010) showed that when infants learned to associate arbitrary features with large and small object sizes, they expected a similar association between those same features and large and small numerosities or durations. In another study, de Hevia and Spelke (2010) showed that after exposure to a series of stimuli with increasing or decreasing numerosities, 8-month-olds failed to dishabituate to sequences of lines changing length in the same direction, but dishabituated to sequences proceeding in the opposite direction. These studies leave open the question of whether infants generate more precise representations such as ratios and multi-item ranks.

In audition, humans and macaques retain representations of pitch-height changes in sequences of tones ('melodic contour'; Brosch, Selezneva, Bucks, & Scheich, 2004; Dowling & Fujitani, 1971; Marvin, 1997; Marvin & Laprade, 1987; Trehub, Thorpe, & Morrongiello, 1987). One study found that these representations can be constructed from and transferred across other auditory continua such as brightness and loudness (McDermott, Lehr, & Oxenham, 2008). Other studies found that adults can compare melodies to line drawings that represent long sequences of pitch-height changes (Prince, Schmuckler, & Thompson, 2009), suggesting a modality-independent representation of height. However, the granularity of these abstract representations of pitch and other auditory contours remains unknown.

In summary, previous studies are consistent with the existence of precise, spontaneous, relative-magnitude representations that can be transferred or mapped across diverse dimensions, but no series of experiments has demonstrated precision, spontaneity, and generality of these underlying representations simultaneously while keeping the behavioral methodology constant. Moreover, to our knowledge, no study has yet explicitly distinguished between ratio-based and rank-order-based representations of magnitude sets as potential candidates for generalized magnitude representations.

1.2. Overview of experiments

We provide evidence that human adults use precise, relative-magnitude information to compare sequences within and across sensory modalities and dimensions. Using a sequence-comparison method, we tested the specific hypotheses that subjects (1) can automatically extract ratio information within visual and auditory modalities and (2) can use it to compare sequences across sensory modalities and across the dimensions of space, time and number.

We created pairs of stimulus sequences containing a randomly generated, standard sequence and a comparison sequence that preserved the standard's abstract structure with varying levels of precision. The comparison could be the same sequence (*Same* sequences, for within-dimension comparisons only), a sequence in which between-item ratios were preserved (*Ratio* sequences), a sequence in which only the between-item ranks was preserved (*Rank* sequences), and a pseudorandom sequence that violated the rank-ordering of the standard (*Different* sequences); see Fig. 1 for an illustration. We predicted that perceived similarity of patterns would decrease as a function of increased information loss from standard to comparison: *Same* > *Ratio* > *Rank* > *Different*.

2. Experiment 1: within-dimension sequence comparisons

In this experiment, sequence pairs were presented in the same stimulus dimension, with separate groups of subjects tested in each. Visual sequences consisted of three squares varying in the dimensions of height or surface area. Auditory sequences consisted of three, band-pass-filtered samples of white noise varying in the dimensions of brightness (center frequency) or loudness (bandwidth and gain). These particular dimensions were chosen for the following reasons: (1) loudness and brightness are subsets of dimensions used in McDermott et al. (2008) and the visual continua of size and height provide intuitive, simple analogues in another sensory modality; (2) they also provide samples of both quantitative dimensions (amounts or intensities) and qualitative dimensions (continuous or categorical features; see Stevens, 1975, and Gati & Tversky, 1982 for further theoretical discussion). Size and loudness are examples of quantitative dimensions while auditory brightness is an example of a qualitative dimension. Object height is interpretable as either, depending upon whether it is measured as a distance from an anchor or a location detected using a filter bank.

2.1. Method

2.1.1. Subjects

Adults from the United States were recruited on Amazon Mechanical Turk; $n = 15$ for each of the stimulus dimensions. Subjects were paid $3.50 (≈$8/h).

2.1.2. Stimuli

Visual stimuli appeared in a white, 600-by-600-pixel (px) window with a black, 1-px-thick border. On each trial, 'Sequence 1' or 'Sequence 2' was printed in the middle of the viewing area prior to each sequence for 750 ms. Sequences consisted of three, 500-ms stimulus intervals separated by 250 ms inter-stimulus intervals.

Magnitude ratios of adjacent stimuli were constrained to be no smaller than 7:8. In the size sequences, squares were constrained

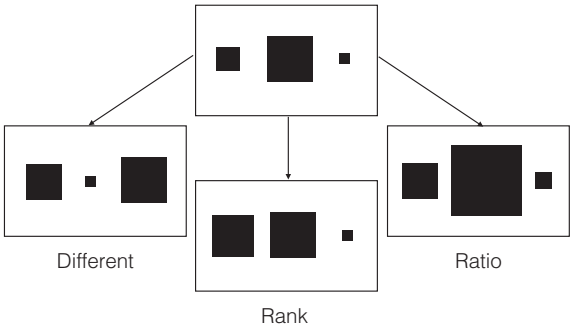

Fig. 1. Examples of sequence types. At the top is the standard sequence with the horizontal axis representing time (left to right). Arrows lead to possible comparison sequences in the *Different*, *Rank*, and *Ratio* pairs.