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Comparative judgments of symbolic and non-symbolic stimuli yield different patterns of reaction times

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ABSTRACT

Are different magnitudes, such as Arabic numerals, length and area, processed by the same system? Answering this question can shed light on the building blocks of our mathematical abilities. A shared representation theory suggested that discriminability of all magnitudes complies with Weber's law. The current work examined this suggestion. We employed comparative judgment tasks to investigate different types of comparisons — conceptual comparison of numbers, physical comparison of numbers and physical comparison of different shapes. We used 8 different size ratios and plotted reaction time as a function of these ratios. Our findings suggest that the relationship between discriminability and size ratio is not always linear, as previously suggested; rather, it is modulated by the type of comparison and the type of stimuli. Hence, we suggest that the representation of magnitude is not as rigid as previously suggested; it changes as a function of task demands and familiarity with the compared stimuli.

1. Introduction

What is the relationship between the ability to distinguish between two numbers and the distance between them? This question attracted much attention in the literature of numerical cognition. Many suggested that this relationship obeys Weber's law and that numerical values are compared similarly to other dimensions (e.g., size). The current study examines these issues, reports deviations from Weber's law and suggests that different dimensions give rise to different comparative functions.

Moyer and Landauer (1967) asked adult participants to compare two Arabic numerals (to choose the numerically larger number). The authors plotted reaction time (RT) as a function of the numerical distance between the to-be-compared numbers and reported that the best fit to describe their data was the equation RT = K * log (larger/larger-smaller) (i.e., the Welford function), which accounted for 75% of the variance. Accordingly, the authors suggested that comparisons of numbers are made "… in much the same way that comparisons are made between physical stimuli such as loudness and length of lines" (p. 1520). The same methodology (i.e., comparative judgments, and plotting RT as a function of the distance or ratio between the compared stimuli) was employed by others and led to the conclusion that the pattern of results was compatible with Weber's law.

Weber's law states that $\Delta I/I = K$. That is, the amount necessary to detect a difference between two stimuli (e.g., ΔI) depends on the initial intensity of the stimulus (e.g., I). The ratio of the just noticeable difference (JND) to intensity is constant (e.g., K). To examine changes in the ability to discriminate between magnitudes, researchers use comparative judgment tasks and examine changes in performance — accuracy and speed of responding (RT) — as a function of the ratio between two magnitudes. The underlying assumption is that RT measures the ability to discriminate between two magnitudes. As such, RT should increase with increase in stimuli ratio because increase in stimuli ratio means increase in the similarity between the to-be-compared stimuli or difficulty to discriminate between them. When RT as a function of ratio was linear it was taken as an indication for compatibility with Weber's law. For example, comparisons of the conceptual size of pictures of objects (Paivio, 1975), words representing different animals (Moyer, 1973), and comparisons of dot arrays by monkeys and humans (Brannon, 2006). Note that all these studies used RT and discussed Weber's law. Hence, in the numerical cognition literature, RT is an acceptable measure of discriminability; Moyer (1973) cites Johnson's (1939) results revealing Weber's law performance in the comparison of two line lengths and using RT as the dependent measure, and Verguts, Fias, and Stevens (2005) cite a work by Festinger (1943) that discusses Weber's law in the context of RT experiments.

On the basis of this common ground, Cantlon, Platt, and Brannon (2009) suggested that all magnitudes are processed by the approximate number system (ANS), the hallmark of which is Weber's law. This shared representation and the compliance with Weber's law are highly

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acceptable principles in the numerical cognition literature and a large number of studies use these assumptions as their point of departure (Beran, Decker, Schwartz, & Schultz, 2011; Buhusi & Cordes, 2011; Droit-Volet, 2010; Möhring, Libertus, & Bertin, 2012; Piazza, 2010; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Piazza et al., 2010; Tokita & Ishiguchi, 2011; Walsh, 2003).

However, this line of evidence has several shortcomings. First, some studies reported the distance effect, but examined only 2–3 different distances (Cohen Kadosh, Henik, & Rubinsten, 2008; Rubinsten & Henik, 2002; Vigliocco, Vinson, Damian, & Levelt, 2002). Under those conditions it is hard to find subtle differences between different magnitudes. Second, in many studies (e.g., Cantlon & Brannon, 2006; Cohen Kadosh et al., 2005; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003; Piazza, 2010) the existence of the distance effect is taken as evidence for compliance with Weber's law. This is an inaccurate statement because Weber's law suggests not only that the discriminability depends on the ratio between the to-be-compared magnitudes, but also that this dependency is *linear*. In studies that tried to fit their data to a linear trend, the value of the fit to Weber's law was around 75–79% (Moyer, 1973; Moyer & Landauer, 1967 — fit to the Welford function; Paivio, 1969), while the fit to Weber's law in comparative judgment of line length was 99% (Moyer, 1973, citing Johnson, 1939). In all of those studies there are no reports of attempting to fit the results to functions other than linear. Thus, deviation from Weber's law is possible. The third shortcoming lies in the fact that most studies in the numerical cognition literature focused on *comparative judgments* of two numerosites or the conceptual size of symbolic stimuli, and compared their results to findings regarding physical sizes such as loudness, brightness, etc., found in *estimation* tasks. Given that different magnitudes were studied using different methodologies, it is problematic to suggest, for example, that comparisons of numbers are made similarly to comparisons between physical stimuli (Moyer & Landauer, 1967, p. 1520; see also Brannon, 2006, for a very similar suggestion).

The current study employed the same method — comparative judgments — with the aim to more accurately describe participants' performance while comparing different stimuli. Specifically, participants were asked to decide which of two stimuli was physically or conceptually larger. The stimuli were single-digit numbers that were compared according to their numerical value (conceptual comparison, e.g., 2 7), or their physical size (physical comparison, e.g., 2 2), or the stimuli were two identical punctuation marks (e.g., #, @, &, etc.) or identical Gibson figures (Gibson, Gibson, Pick, & Osser, 1962) — meaningless shapes that have the same visual complexity as numbers — that were compared according to their physical size. Every participant performed only one condition.

In line with studies mentioned above, we expected performance to comply with Weber's law. Namely, we expected that a constant increase in ratio between two numbers would result in a constant increase in RT. For example, if RT to the pair 2 4 (ratio of 0.5) is 300 ms, and RT to the pair 5 3 (ratio of 0.6) is 350 ms, then RT to the pair 7 5 (ratio of 0.7) is predictable — 400 ms — since for every 10% increment in the numerical ratio, RT increases by 50 ms (a constant). Hence, in the current study we plotted RT as a function of magnitude ratio and fitted it to the function $RT = ax^b + c$, where RT is a measure for discriminability, x is the ratio between the magnitudes (smaller divided by larger) and c is the minimal RT. If the relationship between RT and magnitude ratio is linear, as suggested by previous studies (e.g., Cantlon et al., 2009), and referred to as Weber's law, the exponent b should be 1. Exponent values other than 1 would indicate deviation from Weber's law. Larger exponents mean that the change in RT is not constant and cannot be predicted by a linear function. Plotting RT as a function of magnitude ratio (smaller/larger) has been done in several works. For example, Cantlon and Brannon (2006) had participants compare numerosity of dots (select the array with less dots) and plotted RT as a function of numerosity ratio. They concluded from that linear relationship that their pattern suggested Weber's law.

By finding the exponent (b) for each participant and using its value as a dependent variable, we were able to more thoroughly investigate whether type of stimuli (symbolic or non-symbolic) and type of comparison (physical or conceptual) modulated performance in a comparative judgment task.

The expected results according to the current literature are: (1) there would be no significant difference among exponents of different types of stimuli and comparisons, and (2) these exponents would not be significantly different from 1, suggesting a linear trend and compliance with Weber's law. However, if performance in comparative judgment tasks is modulated by the type of comparison and type of stimuli, we expect the exponents to be different from each other.

2. Experiment 1: conceptual comparison of Arabic numerals

2.1. Method

2.1.1. Participants

Fourteen volunteers (10 females, 4 males), first year students at Ben-Gurion University of the Negev, participated in the experiment for class credit. All participants were native Hebrew speakers and had intact or corrected vision.

2.1.2. Stimuli

Arabic numerals in black Ariel font were presented on a white background, in the same physical size. We manipulated the numerical ratio between the two numbers from 0.1 to 0.8. For example, the ratio of 0.5 was composed of the pairs (2 4), (3 6), etc. For every ratio, we used all the possible pairs (see Table 1). There were 6 pairs of numbers for every ratio. If the number of possible pairs per ratio was smaller than 6, some of the pairs were used more than once. Overall, across all ratios, all the numbers appeared a similar number of times.

2.1.3. Procedure

Participants were asked to decide, as quickly as possible while avoiding errors, which of the two Arabic numerals was numerically

Table 1
Pairs of stimuli by numerical ratio.

Category ratio	Ratio	Large number	Small number
0.1	0.11	9	1
	0.13	8	1
	0.14	7	1
0.2	0.2	5	1
	0.22	9	2
	0.25	4	1
	0.25	8	2
0.3	0.33	3	1
	0.33	6	2
	0.33	9	3
0.4	0.4	5	2
	0.43	7	3
	0.44	9	4
0.5	0.5	2	1
	0.5	4	2
	0.5	6	3
	0.5	8	4
0.6	0.6	5	3
	0.63	8	5
	0.67	3	2
	0.67	6	4
	0.67	9	6
0.7	0.71	7	5
	0.75	4	3
	0.75	8	6
0.8	0.8	5	4
	0.83	6	5
	0.86	7	6

Note. Ratio = (small number/large number) with an accuracy of 2 decimal places.