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Brief article

Asymmetric activation spreading in the multiplication associative network due to asymmetric overlap between numerosities semantic representations?

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ABSTRACT

Simple multiplication facts are thought to be organised in a network structure in which problems and solutions are associated. Converging evidence suggests that the ability for solving symbolic arithmetic problems is based on an approximate number system (ANS). Most theoretical stances concerning the metric underlying the ANS converge on the assumption that the representational overlap between two adjacent numbers increases as the numerical magnitude of the numbers increases. Given a number N, the overlap between N and $N + 1$ is larger than the overlap between N and $N - 1$. Here, we test whether this asymmetric overlap influences the activation spreading within the multiplication associative network (MAN). When verifying simple multiplication problems such as 8×4 participants were slower in rejecting false but related outcomes that were larger than the actual outcome (e.g. $8 \times 4 = 36$) than rejecting smaller related outcomes (e.g. $8 \times 4 = 28$), despite comparable numerical distance from the correct result (here: 4). This effect was absent for outcomes which are not part of either operands table (e.g., $8 \times 4 = 35$). These results suggest that the metric of the ANS influences the activation spreading within the MAN, further substantiating the notion that symbolic arithmetic is grounded in the ANS.

1. Introduction

The understanding of symbolic numbers and the acquisition of arithmetical skills are thought to be grounded on a semantic core system (Butterworth, 2010; Feigenson, Dehaene, & Spelke, 2004; Nieder & Dehaene, 2009; Piazza, 2010; Stoianov & Zorzi, 2012), which is hypothesised to represent numerical magnitude in an approximate, analog fashion (Dehaene, 2003). Converging evidence suggests a functional connection between this core system, henceforth referred to as the approximate number system (ANS), and the symbolic system that supports mathematics (Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Halberda, Mazzocco, & Feigenson, 2008; Kallai, Schunn, & Fiez, 2012; Lourenco, Bonny, Fernandez, & Rao, 2012). In this study we tested whether the underlying metric of the ANS interacts with the internal structure of the multiplication associative network (MAN), i.e. the memory system representing one-digit multiplication problems.

The semantic representation of numerical magnitude is often conceptualised as a spatially oriented analogue number line (for a review see, Dehaene, 2003). Although

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diverging on the exact format of the metric underlying the number line the currently most influential theories (log-Gaussian model, Dehaene, 1992; scalar variability model, Gallistel & Gelman, 1992, 2000; numerosity code, Zorzi, Stoianov, & Umiltà, 2005) share the notion that the overlap between the representations of two adjacent numbers increases as the magnitude of the numbers increases. Namely, given a number N, the overlap between the representations of N and $N + 1$ is larger than the overlap between N and $N - 1$.

When solving simple one-digit multiplications adults mainly retrieve the correct result from the MAN (see for example, Lefevre et al., 1996; Smith-Chant & LeFevre, 2003). The MAN is conceptualised as a associative network, in which the representations of operands and results are highly interconnected (see for example, Ashcraft, 1987; Campbell, 1995; Verguts & Fias, 2005). The retrieval process is thought to be driven by an automatic activation spreading within the MAN (Galfano, Penolazzi, Vervaeck, Angrilli, & Umilta, 2009; Galfano, Rusconi, & Umiltà, 2003; Niedeggen & Rosler, 1999; Rusconi, Galfano, Rebonato, & Umiltà, 2006; Rusconi, Galfano, Speriani, & Umiltà, 2004). Namely, following the presentation of two operands (e.g., 8×4), activation is spread so that a series of possible results (likely the product, e.g. 32, and the multiples of the operands close to it, e.g. 24, 28, 36, and 40) is activated, and then the highest activated result is retrieved as the actual result. Since the MAN is a highly interconnected associative network, activation can spread both from operands to results and between results themselves (see, for example, the *network interference model*, Campbell, 1995).

Since arithmetic is grounded in the ANS and numerical magnitude appears to be automatically activated (Kallai et al., 2012; Piazza, Pinel, Le Bihan, & Dehaene, 2007), it is reasonable to suppose that the metric underlying the ANS interacts with the associative architecture of the MAN. Some models conceptualise the MAN in a purely abstract fashion, not taking into account the particular metrical characteristics of the mental magnitude representation (see for example, Ashcraft, 1987). However, two associative computational models (MATHNET, see McCloskey & Lindemann, 1992; semantic/symbolic model of Stoianov, Zorzi, & Umiltà, 2004; for a review see Zorzi et al., 2005) assume that the MAN encodes a semantic representation. Campbell's model (1995) also assumes that a magnitude system contributes to activate the problem nodes within the MAN. Consistently with these models, we assume that this semantic representation affects the retrieval process within the MAN. In particular, we hypothesised that the asymmetric overlap between numbers with increasing overlap as numerical magnitude increases produces an asymmetry in the activation spreading within the MAN during the retrieval process. Namely, for a given multiplication problem (e.g., $8 \times 4 = 32$), multiples of the operands larger than the correct outcome (i.e., 36) would receive higher activation spreading due to the larger overlap on the ANS and thus become more co-activated compared to multiples smaller than the correct outcome (i.e., 28). Consequently, larger proposed results (e.g., $8 \times 4 = 36$) should exhibit stronger interference with the correct outcome and be rejected slower than smaller ones (e.g., $8 \times 4 = 28$).

2. Methods

2.1. Participants

Thirty-four Thai students of the Burapha University participated in the present experiment as volunteers (23 females; mean age: 21.4, SD = 1.1). All participants had normal or corrected-to-normal vision.

2.2. Material

Multiplications from 3×3 to 8×8 were used as stimuli (for non-tie problems both operand-orders were presented). The operands 2 and 9 were not used because of their smaller and larger associated outcomes are in the 1 and 10 tables, respectively. For each problem we presented 8 correct equations (e.g., $8 \times 4 = 32$), 4 multiple incorrect equations (e.g., $8 \times 4 = 40$), and 4 neutral incorrect equations (e.g., $8 \times 4 = 39$). In multiple incorrect equations the proposed result was a multiple of one of the operands, whereas in neutral incorrect equations the proposed result was the "multiple incorrect result" ±1. Namely, given a problem (e.g., 8×4), the 4 incorrect multiple results were: one of the two above multiples (e.g., $8 \times 4 = 40$ or $8 \times 4 = 36$) or one of the two below ones (e.g., $8 \times 4 = 24$ or $8 \times 4 = 28$). The 4 incorrect neutral results were the multiples ±1: $8 \times 4 = 39$, $8 \times 4 = 35$, $8 \times 4 = 25$, $8 \times 4 = 29$. Participants performed 4 blocks with 144 problems each. In each block, there were: 72 correct problems, 18 above and 18 below multiples, 18 above and 18 below neutral results. In each block each problem was presented four times: twice with the correct result, once with a multiple incorrect result, and once with a neutral incorrect result. For each problem the four neighbour multiples (and the four neutrals) were randomly assigned to different blocks. The order in which problems and conditions were presented varied randomly for each participant and was balanced across blocks.

2.3. Procedure

During the experiment participants sat alone in a partially sound-proof room at about 60 cm from the monitor. The experiment started with a practice block (10 trials) in which one of the operands was either 2 or 9. The stimuli (0.95 degree of visual angle) were sequentially presented at the centre of the monitor. Each trial started with a fixation point ("#") presented for 1 s, followed by the first operand, the sign ("×"), the second operand, and the equal symbol ("="), all presented for 300 ms each. After the offset of the equal symbol the proposed result was presented and participants had 2 s to respond. For trials in which no timely response was produced an omission feedback (1 s) appeared asking for faster performance. The intertrial interval was of 1500 ms. Participants responded by pressing the "Z" and "M" keys of the keyboard. Response key assignment to "yes" and "no" answers was