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Research report

Core number representations are shaped by language

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ABSTRACT

Language and math have been predominantly related through exact calculation. In the present study we investigated a more fundamental link between language and math: whether the most basic quantity representation used for the contrast of numerosities could be shaped by language. We selected two groups of balanced, equally proficient Basque-Spanish bilinguals. Crucially, the two groups differed with respect to the language in which math had been learned at the point of earliest formal instruction in mathematics (Language of learning Math – LL^{math}). They performed a simple comparison task between pairs of Arabic digits related through the decimal system or through the vigesimal system. The vigesimal system is retained in Basque for the naming of certain numerals, while for other numerals the decimal system is used, just as for all Spanish number words. Event-related potential (ERP) distance effects were taken as the dependent variable, indexing the activation of quantity. Results showed an N1–P2 distance effect during the comparison of digit pairs related through the base-10 system in both groups. Importantly, this N1–P2 effect appeared only for the group whose LL^{math} was Basque when base-20 related digits were compared, even if both groups were perfectly fluent in Basque. Thus the early N1–P2 component appears to be sensitive to verbal components contained in quantity representation. Since the task did not contain any verbal input, the present data suggest that quantity representation may have verbal traces inherited from early learning. In turn, LL^{math} should be the optimal medium for numerical communication.

1. Introduction

Bilingual brokers in stock exchange markets perform rapid calculations while they communicate in the primary language of the market. However, even if they master both languages, those calculations may involve different processes, depending on the language required. We propose that the numeric system should optimally flow in the language in which math was learned (herein, LL^{math}). The present study addresses idiosyncrasies of math in bilinguals and questions such issues as magnitude code permeability to non-numeric information and the nature of numerical representations.

There are different views regarding a possible linguistic prelude to the development of numerical representations (Butterworth, Reeve, Reynolds, & Lloyd, 2008; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Gordon, 2004; Pica, Lemer, Izard, & Dehaene, 2004). The very restricted set of number-words in Brazilian Amazonian tribes implies

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differences for exact, but not approximate, calculation (Gordon, 2004; Pica et al., 2004). Speakers of Munduruku for example (Pica et al., 2004) do not differ from controls when approximately comparing two quantities, but fail in doing simple exact arithmetic with operands out of their counting range. Additionally, language and numerical cognition appear to become linked in children before the initiation of formal education when they start to master counting: while learning the counting sequence, children slowly achieve the understanding that the last number word used in a count tells how many items there are, the cardinal word principle. In turn, learning to count involves, in part, learning a mapping from the preverbal numerical magnitudes to the verbal and written number symbols, and the inverse mappings from these symbols to the preverbal magnitudes (Gelman & Gallistel, 1978; Wynn, 1990).

Aside from questions about the Whorfian linguistic relativity principle, which states that speakers from different languages think differently (Whorf, 1940, 1956), knowing whether bilinguals process math differentially as a function of their languages can provide fruitful information on math and language dependencies. Evidence that numerical representations and processes depend on native language (L1) remains mixed, and usually, studies target the distinction between exact (i.e., telling the exact solution to $8 \times 7 = 56$ *vs* 58) and approximate calculations (i.e., choosing the closest, approximate solution to problems such as $8 \times 7 = 60$ *vs* 45 or estimating the root square of 65), which restricts language dependence, if any exists, to exact calculations (Frenck-Mestre & Vaid, 1993; Dehaene et al., 1999; Spelke & Tsivkin, 2001; Bernardo, 2001; Campbell & Epp, 2004; Rusconi, Galfano, & Job, 2007; Salillas & Wicha, 2012). Exact arithmetic can be related to language because arithmetic facts (i.e., exact multiplication) are learned and ultimately retrieved verbally. Therefore, research on math in bilinguals has targeted the possible L1 predominance in the memorization and retrieval of arithmetic facts, has explicitly varied the linguistic code with L1/L2 input as a variable, and has used behavioral (Frenck-Mestre & Vaid, 1993; Spelke & Tsivkin, 2001; Bernardo, 2001; Campbell & Epp, 2004; Rusconi et al., 2007), neuroimaging (Dehaene et al., 1999; Venkatraman, Siong, Chee, & Ansari, 2006; Grabner, Saalbach, & Eckstein, 2012) and event-related potential (ERP) methods (Salillas & Wicha, 2012). The current view is that after experimental training in novel exact arithmetic facts, those facts remain linked to the language used during training (Spelke & Tsivkin, 2001), and this process is subserved by left-lateralized linguistic-related areas (Venkatraman et al., 2006). These results indicate that exact arithmetic depends on language; however, approximate arithmetic would operate independently from the language of training. Without the use of explicit training, another group of studies have addressed bilingual math processing through the observation of actual L1 *vs*. L2 performance in math. These experiments tested participants whose L1 was also the language in which the participants learned math. Better arithmetic fact representations in L1 were found (Frenck-Mestre & Vaid, 1993; Campbell & Epp, 2004 or Rusconi et al., 2007).

Only two studies to date (Bernardo, 2001; Salillas & Wicha, 2012) have addressed the effects of early and sustained learning on life-long arithmetic representations. Using the time fine-grained ERP technique, Salillas and Wicha (2012) dissected the electrical brain response (i.e., underlying processes) to arithmetic fact solutions presented in what was called "Language of Learning Arithmetic (L+) *vs* the other language (L−)". Spreading of activation between multiplication problems and their solutions showed a very different ERP pattern depending on whether they were presented in L+ or L−. The study concluded that arithmetic memory networks depend on early learning (i.e., L+). The present study aimed to investigate whether the most basic numerical representation [i.e., the quantity code, an analogical representation of numerical quantity very similar to the one observed in animals and in young infants, organized by numerical proximity and with increasing fuzziness for larger numbers (Dehaene, 1996, 2001)] has also traces of language inherited from early learning. This code is proposed to be innate and abstract, and its penetrability to symbols is the topic of current advances in math cognition (Dehaene, 2009; Nieder & Dehaene, 2009). We addressed this issue by studying whether numerical words (number linguistic symbols) could have left a trace on the quantity code.

Bilingualism and multilingualism increase the one-to-one mapping between number words and magnitude representations. That is, bilinguals have more than one word to refer to each numerosity, thus opening the questions of which of those linguistic codes connect to *core* math functioning (i.e., the quantity representation), when that code predominance is settled, and how long that predominance lasts. Given the exposure to number words associated to quantity in a particular language during early learning, number representations could have been shaped by that particular language. During development core magnitude representation evolves into a spatial mental image: the quantity code incorporates a new spatial component that moreover, depends on reading habits. This suggests that the quantity code is not a fixed representation and that it is malleable by different information during learning, showing individual and cultural differences (Dehaene, Bossini, & Giraux, 1993; Seron & Fayol, 1994). This representation appears after number words or Arabic symbols are memorized and then used for counting. Therefore, permeability to language in the magnitude code is possible as well. However, linguistic prints in the quantity code are not contemplated by the existing theoretical approaches, although the connection between symbol and quantity are increasingly studied (Butterworth, 2010; Piazza, 2010) and included as an explanation for math disorders (Iuculano, Tang, Hall, & Butterworth, 2008; Butterworth, 2010). Thus a broader concept, such as the language of learning math (LL^{math}), rather than just the language of learning arithmetic (L+), could be crucial in different aspects of math functioning and applicable beyond simple arithmetic fact retrieval. While L+ implied the language used in the core verbal storage of arithmetic facts, LL^{math} refers to a more extensive linguistic context for early mathematical learning. Generally, LL^{math} would coincide with the current language used for counting, and for fact retrieval (L+). The subsequent language used for very extensive math learning during higher education or work activity could possibly modify the dominance pattern for math.