Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Research report

Core number representations are shaped by language

Elena Salillas [a,*] and Manuel Carreiras [a,b]

[a] Basque Center on Cognition Brain and Language, San Sebastian, Spain
[b] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

ARTICLE INFO

Article history:
Received 8 October 2012
Reviewed 21 December 2012
Revised 21 March 2013
Accepted 17 December 2013
Action editor M.J. Tainturier
Published online 31 December 2013

Keywords:
Bilingualism
Math cognition
Quantity code
Distance effect
ERPs

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

* *Corresponding author*. Basque Center on Cognition Brain and Language, Paseo Mikeletegi 69, 2nd Floor, San Sebastian 20009, Spain.
E-mail address: e.salillas@bcbl.eu (E. Salillas).
0010-9452/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cortex.2013.12.009

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.

For this study, we used Arabic digit comparison: a task considered to tap into magnitude processing and independent from language, especially when the input does not imply a verbal code (e.g., Dehaene & Cohen, 1995; see also Dehaene, Piazza, Pinel, & Cohen, 2003). Preverbal children and nonhuman primates compare sets on the basis of number (e.g., Feigenson, Carey, & Spelke, 2002; Jones & Brannon, 2012; Barnard et al., 2013) and numerical comparison activates bilateral parietal areas that are independent from language (for a metanalysis see Dehaene et al., 2003). The effects of LL^{math} on number semantics were measured using the well-documented *distance effect* (Moyer & Landauer, 1967) as a dependent measure of access to number semantics (quantity code). The distance effect, by which close numbers are more difficult to compare than distant numbers, indexes quantity manipulation and has been widely studied using behavioral methods (e.g., Moyer & Landauer, 1967; Dehaene, Dupoux, & Mehler, 1990), computationally modeling (e.g., Verguts & Fias, 2004; Verguts, Fias, & Stevens, 2005; Van Opstal, Gevers, De Moor, & Verguts, 2008) and functional magnetic resonance imaging (fMRI). The distance effect can also be captured using ERPs (Libertus, Woldorff, & Brannon, 2007; Paulsen & Neville, 2008; Cao, Li, & Li, 2010; Liu, Tang, Luo, & Mai, 2011). This effect has been proposed to have a brain locus in the intraparietal sulcus (IPS) (see metanalysis by Dehaene et al., 2003), which is an area where basic quantity processing takes place. Previous studies have shown distance effects on the N1 to P2 transition and P2p amplitudes during numerical comparison (Dehaene, 1996; Temple & Posner, 1998; Libertus et al., 2007; Cao et al., 2010). Since the first ERP study on the distance effect (Dehaene, 1996), close and far distances have been reported to differ at approximately 200 msec post-stimulus in comparison tasks. Temple and Posner (1998) found that modulations in the complex N1–P2p are similar between 5-year-old children and adults but differ between symbolic and non-symbolic stimuli.

A major focus of study has been on possible differences in the P2p distance effect, depending on the format in which numerosities are presented. The goal was to establish whether the quantity representation is abstract or non-abstract (e.g., Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Cohen Kadosh, Muggleton, Silvanto, & Walsh, 2010; Cohen Kadosh, Bahrami, Walsh, Butterworth, & Price, 2011). Libertus et al. (2007) found no differences in the N1 to P2p transition (180–210 msec) and P2p (210–250 msec) distance effect between symbolic and non-symbolic formats when visual variables were controlled.

Literature on attention reports the N1 (and the P1) as an obligatory, exogenous sensory component that is independent of top-down control. Nonetheless it also entails a summation of other components which are not necessarily exogenous (Luck & Kappenman, 2012) thus being affected by top–down processes and having shown linguistic effects (Kretzschmar, Bornkessel-Schlesewsky, & Schlesewsky, 2009). The early P2 component that follows can be also modulated by high cognitive functions, including linguistic variables (e.g., Federmeier & Kutas, 2002; Barber, Ben-Zvi, Bentin, & Kutas, 2011). In the context of numerical experiments and specifically in numerical comparison tasks, the existing data suggest that numerical semantic processing is indexed by a notation-independent neural process: the electrophysiological numerical distance effect that starts approximately 180 msec after stimulus onset and is reflected in differences in the transition between the first ERP negativity (N1) to the second posterior positivity (P2p) (N1–P2p: 174–202 msec) and on the P2p (206–238 msec) component itself. In contrast, Cao et al. (2010) showed differences for Chinese number symbols but also found an N1–P2p and P2p distance effect for Arabic input. Cao and collaborators noted that notation and semantic effects interact and co-occur at these latencies, and therefore suggested, contrary to Libertus et al. (2007), a notation dependent access to semantics. The question of whether quantity representation is abstract (McCloskey, 1992; Dehaene & Cohen, 1995; Piazza, Pinel, Le Bihan, & Dehaene, 2007) or whether it is multiple and format dependent (Cohen Kadosh et al., 2007; Cohen Kadosh et al., 2010; Cohen Kadosh et al., 2011) remains unanswered. Hsu and Szücs (2012) studied the distance effect during an adaptation task, which implies a non-intentional magnitude comparison. These authors again found distance effects evoking ERP modulations in latencies approximately 200 msec as well as oscillatory electroencephalography (EEG) activity at this latency. Taken together, these studies suggest an effect approximately 200 msec for the automatic analysis of numerical magnitude. In agreement with these previous studies, we focused on the distance effect within the N1 to P2 transition (hereafter N1–P2) and P2p latency bands and studied the effect as a dependent variable indexing magnitude analysis.

This study capitalized on the coexistence of two numeral word systems in Basque-Spanish bilingualism: all Spanish number words and some Basque number words include the name of the decade and the unit [e.g., “cuarenta y seis” “Berrogeitasei” (*forty and six*) for 46 following the decimal system]. Importantly, however, Basque retains a partial vigesimal (base 20) system of number names together with the decimal system. The number 56 is expressed as “berrogeitahamasei”(*forty ten and six*) as a compound word. Evidence about the impact of the way in which we name digits on how we operate with them is mixed. Some studies have shown that this influence is mediated by input–output processes, namely that language effects disappear when a motor instead of verbal response is required (Brysbaert, Fias, & Noel, 1998). Other studies have shown than unit-decade compatibility effects [compatible comparisons in which separate decade and unit comparisons lead to the same decision (32_47, $3 < 4$ and $2 < 7$) are faster than incompatible trials (37_52, $3 < 5$, but $7 > 2$)] vary depending on the named number word when using Arabic digits (Nuerk, Weger, & Willmes, 2005; Pixner, Moeller, Hermanova, Nuerk, & Kaufmann, 2011). Given the response dependencies on these word-to-math processes, electrophysiological evidence can be especially appropriate for their study. On the other hand, the way in which these word-to-math effects occur in bilinguals can supply crucial information on the origins and evolution of these possible linguistics traces. We studied brain signatures of these number word systems while processing the corresponding Arabic numbers in two groups of fluent bilinguals that only differed in their LL^{math}.

Thus, taking advantage of the coexistence of two number word systems in Basque-Spanish bilinguals, we investigated the possibility that LL^{math} number words left linguistic prints in the quantity code. This was done through the observation of the differences in the ERP distance effects between the two groups with differing LL^{math}. Specifically, we attended to differences in the distance effects for digits pairs linked through base 20 number words, which are restricted to the Basque language. In contrast, and for the same reason, the two groups should show similar electrophysiological response to the distance between digits that are linked through decimal number words, because they are common to both languages. Both the N1 to P2 and P2p distance effects were targeted as a reflection of the access to magnitude in two phases or temporal windows. We hypothesized that 1) If number words corresponding to LL^{math} are just activated during the comparison of Arabic digits, ERPs to digits that are linked through the Basque wording system should differ from ERPs to digits that are linked through the Spanish wording system, depending on the LL^{math}. In this case, ERPs modulations by the numerical distance between the digits should be independent from the LL^{math}. LL^{math} would have a simpler role, modulating the retrieval of number words during the comparison task, and distance effects would appear indistinctly. Specifically N1–P2 or P2p components would appear overall modulated by the activation of the corresponding number word; 2) But most importantly, if ERPs *distance effects* to Arabic digits related through the vigesimal wording system differ as a function of the participants' LL^{math}, then LL^{math} words would have left long-term traces in the *semantics* of numbers during early learning. This would be evidenced by a differential modulation of the N1–P2 and/or the P2p by numerical distance, depending on the corresponding number word, and crucially, depending also on the LL^{math}.

2. Methods

2.1. Participants

Eighteen proficient Spanish-Basque bilinguals participated in this study. The average age of acquisition of L2 Basque was 1.5 year (minimum 0 year, maximum 6 year). Nine participants reported learning math at school in Spanish only (LL_S^{math} group) and nine reported learning math at school in Basque only (LL_B^{math} group). LL^{math} was thus assessed through the question: "In which language did you learn math?". In addition, they were asked: "Which language do you use to do calculation?"; "In which language do you count?" and "In which language do you do multiplications?". Three participants in the LL_B^{math} group reported a mismatch between LL^{math} and the current language used for counting or calculation. Some of them reported that although they overtly use another language for math communication, they covertly use LL^{math}, for mathematical thinking.

The groups were equivalent in proficiency: LL_S^{math} proficiency in Spanish, as measured by the Boston Naming Test (BNT) (Kaplan, Goodglass, & Weintraub, 1983; for other uses of the BNT as a measure of proficiency see e.g., Moreno & Kutas, 2005 or Salillas & Wicha, 2012), was 54.8 (2.52) and in Basque was 48.8 (3.56) ($t = 2.29$; $p = .05$); for the LL_B^{math} group, BNT scores were 53.4 (2) and 50.2 (3.63) ($t = 5.6$; $p < .001$) for Spanish and Basque, respectively. Thus, both groups were slightly more proficient in Spanish and were equivalent in relative proficiency ($t = 1.96$, $p = .09$). On average, the LL_B^{math} group self-reported using Basque 39% of the time and Spanish 61% of the time. The LLs^{math} group self-reported using Basque 44% of the time and Spanish 56% of the time (for percentage of use as a measure of proficiency see e.g., Chauncey, Grainger, & Holcomb, 2008).

2.2. Stimuli

One hundred and forty-four experimental pairs of digits were constructed according to the verbal forms in Spanish and Basque. These pairs were of two types (Table 1, Supplemental material): A) **COMMON PAIRS**, whereby 72 pairs were constructed according to the decimal system, which is common to the verbal form in Basque and Spanish. For example, the structure for the verbal form of "forty-six" is the same in both Spanish ("cuarenta y seis") and Euskera ("Berrogeitasei"). Each pair to be compared consisted of the whole number (e.g., 65) as the first number and one of the two components of the number word as the second number (e.g., 60 or 5), leading to pairs with two different numerical distances between the first and second number to be compared. This led to COMMON CLOSE PAIRS such as 65–60, 46–40, or 85–80, and COMMON FAR PAIRS such as 65–5, 46–6, or 85–5. B) **BASQUE PAIRS**, whereby 72 pairs were constructed according to the Basque expression of the number, based on the vigesimal (base 20) system, but implying the use of the closest even decade. For example, **56** is "cincuenta y seis" in Spanish (fifty-six), but is "berrogeitahamasei" in Basque, which also implies the name "ten" (hamar) and "six" (bost) for sixteen. Similarly, each pair to be compared consisted of the whole number (e.g., 78) as the first number to be compared and the following even decade (60 or 10) as the second number. This led to BASQUE CLOSE PAIRS such as 75–60, 56–40, and 95–80, and BASQUE FAR PAIRS such as 75–10, 56–10, and 95–10. Therefore, to construct material related to the word form, the number of possible pairs was limited. Nevertheless, close and distant pairs were different enough to generate distance effects and were in a comparable range based on the absolute distance

Table 1 – Characteristics of the stimuli. Examples: 75–60 – Basque pair, close distance; 75–10 – Common pair, far distance; 65–60 – Common pair, close distance; 65–5 – Common pair, far distance

		Ratio	Absolute difference	Log (diff)	Diff (log)
Basque pairs	Close	.77	14.8	1.16	.14
	Far	.15	54.8	1.70	.78
	Difference	.62	40	.53	.65
Common Pairs	Close	.90	5	.62	.05
	Far	.09	50	1.65	1.08
	Difference	.81	45	1.03	1.03

Note: *Ratio*: second number divided by the first number for each condition. *Absolute difference*: first number minus second number for each condition. *diff (log)*: difference between the base-10 logarithms of the numbers; *log (diff)*: logarithm of the difference of the raw numbers.

and results (Table 1). A pair type (Basque, Common) × distance (close, far) ANOVA on the items showed that the interaction type of pair × distance was not significant ($F_{1,35} = .7$, $p = .4$). Importantly, the hypothesis and relevant contrast were based on a between-subject factor with identical items for each group of participants.

2.3. Procedure

In all experimental items, the larger number (e.g., 68) was presented first. In this way, the smaller number was always a base-10 digit. This was intended to activate differential base-20 or base-10 quantity-related processes from the beginning of the comparison. Additionally, this also allowed the target to remain a base-10 number, which is common to both languages and all the experimental items. To avoid the inference of any rule, 144 fillers in the same order (large to small) and a pool of 288 fillers in the opposite order (small to large) were added. These filler pairs did not follow any verbal form relationship and had random distance between the first and second number.

Each of the 576 trials consisted of a fixation point that appeared for 1000 msec. followed by a blank screen for 350 msec (Fig. 1). The first digit was then presented and remained on the screen for 300 msec. The second number appeared for 300 msec. The trigger to the EEG was sent with the appearance of the second number, and after a blank screen for 700 msec, a question mark signaled the request of a delayed response. The task of each participant was to decide whether the second number was bigger or smaller than the first number by pressing one of two buttons.

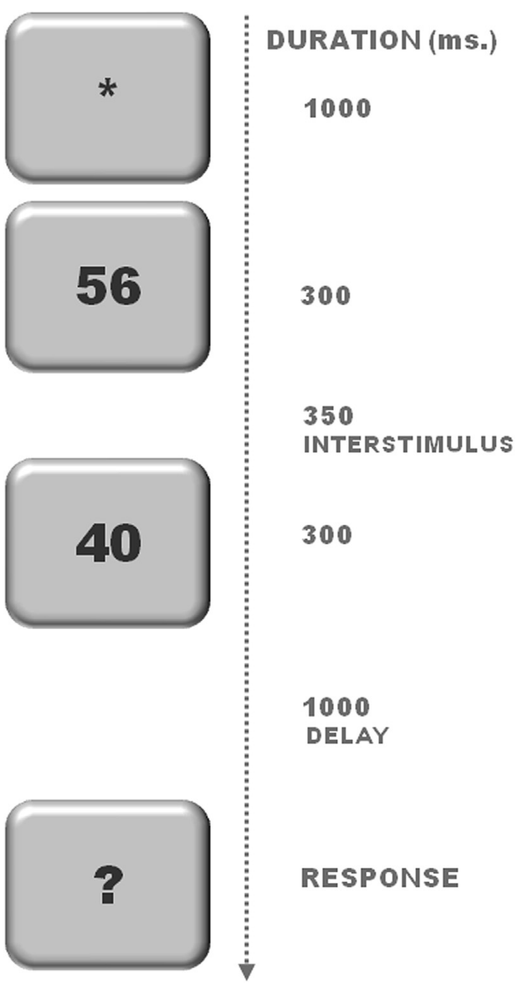

Fig. 1 – Example of one of the trials.

2.4. EEG recording and analysis

The EEG was recorded from 27 scalp electrodes embedded in an Easy-Cap in a 10-system array, which was referenced on-line to the left mastoid. Six free electrodes were used to record blinks (below the eye), horizontal eye movements (outer canthi), and left and right mastoid processes were used as a reference. Electrode impedances were maintained below 5 kΩ. The EEG was amplified with Brain Amp amplifiers, with the band pass set from .01 to 100 Hz, and sampled at a rate of 500 Hz. The output of the bioamplifiers was fed into a 32 channel 12-bit analog-to-digital converter on a PC computer. Presentation software was used to present visual stimuli and record behavioral responses, and *Brain Vision Recorder* software was used to deliver event and timing codes to the data acquisition PC synchronously with the onset of EEG activity to events of interest. Data were re-referenced to the algebraic sum of the left and right mastoids, averaged for each experimental condition, and time-locked to the onset of the second number. A digital band-pass filter set from .1 to 30 Hz was used on all of the data prior to running analyses to reduce high frequency content that was irrelevant to the components of interest. Baseline correction used the 100 msec pre-stimulus. Trials with artifacts due to eye movements, excessive muscle activity, or amplifier blockage were eliminated offline before averaging to ensure roughly an equal loss of data across all conditions. Artifact rejection criteria were a minimum to maximum baseline-to-peak allowed voltage of ±70 μV, a maximum voltage gradient of 75 μV per sample point, a maximal difference of 150 μV in intervals of 100 msec and a minimum voltage of .5 μV in intervals of 50 msec. All electrodes were assessed for artifacts. Analyses were reported for each critical stimulus relative to a 100 msec pre-stimulus baseline. The 27 electrodes were grouped for statistical analyses in two regions of interest (ROIs) with ten electrodes each: ANTERIOR (Fp1, Fp2, F3, F4, F7, F8, FC1, FC2, FC5, and FC6) and POSTERIOR (CP1, CP2, CP5, CP6, O1, O2, P4, P7, and P8 Pz).

A main Analysis of Variance (ANOVA) analysis implied a 2 (type of pair: Common/Basque) × 2 (distance: close/far) × 2 (anteriority: anterior/posterior) × 10 (electrode) design. The two groups were taken as between-subjects variable (LL_S^{math}/LL_B^{math}). Mean amplitudes in the latency bands for the N1–P2 (180–210 msec) and P2p (210–250 msec) were the two dependent variables in this analysis. Where no distance effects were found, a fractioned latency band analysis was performed contrasting averaged amplitude for close *vs* far distance in anterior and posterior electrodes, separately. Five consecutive latency bands ranging in 20 msec windows from 130 to 210 msec were analyzed.

In order to rule out a possible influence of minimal linguistic dominance differences between the bilingual participants, regression analyses were performed between the N1–P2 or P2p distance effect (for the conditions and electrodes showing significant effects) and the different language-use variables: Age of Acquisition, relative percentage of use between Spanish and Basque, relative proficiency between Spanish and Basque and overall proficiency (averaged Spanish and Basque BNT scores).

In an additional analysis, the ratio between the to-be-compared numbers was taken as a parametric value by dividing the averaged value of the second number of the pair in each condition (Common close; Common far; Basque close; Basque far) by the averaged value of the first number. This gave a four-value variable that was correlated with the N1–P2 amplitude for each subject. Further, another ANOVA contrasted the two high ratios and the two low ratios for this component (2 – high/low ratio × 2 – value 1/value 2). These last analyses aimed to disentangle whether N1–P2 amplitudes were sensitive to a continuous variation in ratio between the number pairs (i.e., distance) and were not due to other variables (i.e., perceptual). For all analyses, only significant effects and relevant non-significant effects are reported.

3. Results

3.1. LL^{math} verbal form of a digit determines core magnitude effects

The N1–P2 amplitude (180–210 msec after the digit) was modulated by the distance between the digits and this modulation depended on the type of pair and the LL^{math} (pair × distance × group interaction: $F_{1,16} = 6.3$, $p = .02$) (Fig. 2, see also Supplemental behavioral data). A main effect of distance was found for the LL_S^{math} group ($F_{1,8} = 8.22$, $p = .02$) although this effect was significantly dependent on the digit pair type (distance × pair interaction: $F_{1,8} = 9.87$, $p = .014$). An early access to number semantics was reflected through more positive amplitudes for close numerical distances than far numerical distances only for Common pairs in the LL_S^{math} group ($F_{1,8} = 12.57$, $p = .008$). This distance effect was absent in Basque pairs ($F_{1,8} = .38$, $p = .5$). For the LL_B^{math} group, both Common and Basque pairs showed distance effects in the N1–P2 amplitude (main distance effect: $F_{1,8} = 39.76$, $p < .001$; Basque pairs: $F_{1,8} = 10.61$, $p = .01$; Common pairs: $F_{1,8} = 6.68$, $p = .03$). All distance effects were widely distributed across the scalp and presented anterior maxima (Fig. 2). No main effect of pair or group × pair interaction was significant (Fs < 1). Participants whose LL^{math} (Basque) mismatched their current language for counting (Spanish) also showed N1–P2 modulations by distance in the Basque pairs (see Table S3). A closer view at fractioned latency bands of 20 msec between 130 and 210 msec showed no trace of an N1–P2 modulation by the distance for Basque pairs in LL_S^{math} in either anterior or posterior sites (20 msec fractioned latency bands from 150 to 230 msec showed a maximum effect of $F_{1,8} = 2.25$, $p = .17$ in 170–190 msec). In an additional analysis, distance was taken as a parametric numerical value according to the averaged ratio for each of the distances and pairs (Basque pairs close: ratio = .77; Basque pairs far: .15; Common pair close: .90; Common pair far: .09). A significant correlation between the ratios and the reported N1–P2 distance effects was found ($r = .28$, $p = .016$; $R = .28$, $p = .015$ with all pairs included, and $r = .37$, $p = .005$; $R = .34$, $p = .01$ excluding the Basque pairs for the LL_S^{math} group) (Fig. 3). In fact, the closest ratio values marginally differed in the elicited N1–P2 amplitude ($F_{1,17} = 3.6$, $p = .07$) both for the highest and the lowest ratios (interaction $F_{1,17} = 1.8$, $p = .2$ n.s.). This analysis further demonstrates that number semantics had modulated the N1–P2 amplitude (Libertus et al., 2007; Cao et al., 2010) rather than a perceptual matching effect.

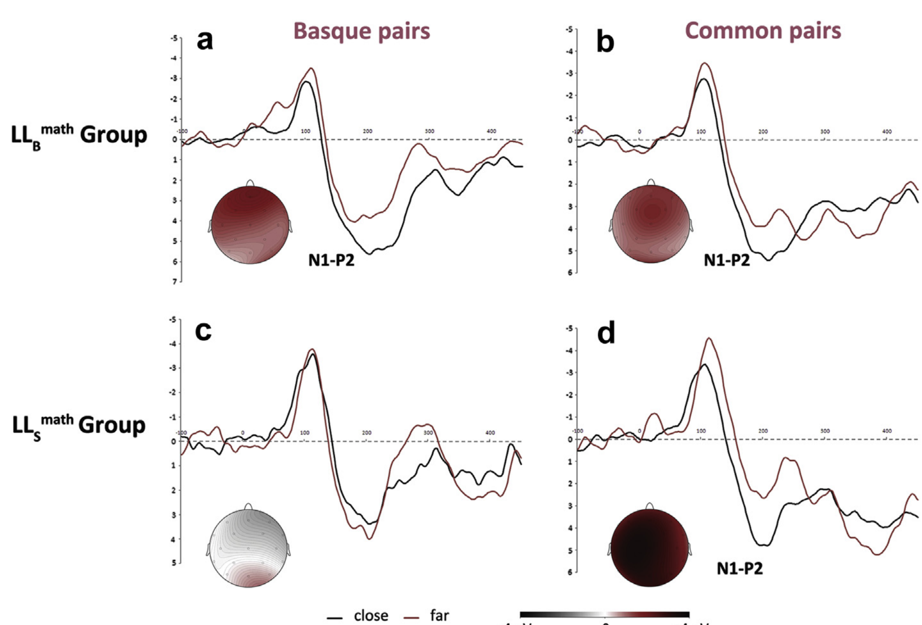

Fig. 2 – The ERP distance effect for the N1–P2 component. The N1–P2 component yielded larger amplitudes for close pairs (i.e., early distance effect) only in the LL_B^{math} group for Basque pairs (a) and in both groups for Common pairs (c and d). Pooled anterior electrodes and difference voltage maps are displayed.

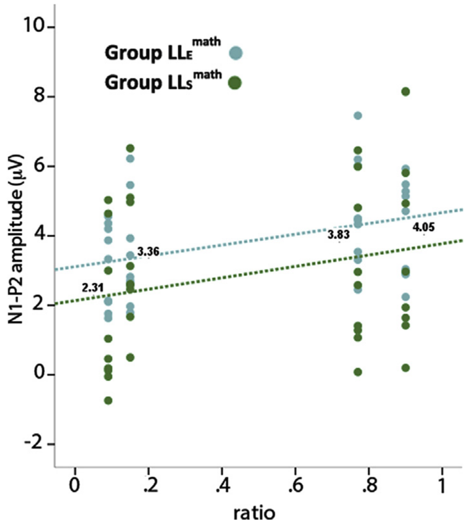

Fig. 3 – Parametric analysis between the ratio for each pair and distance and N1–P2 amplitudes. Basque close: ratio = .77; Basque far: .15; Common close: .90; Common far: .09. Average amplitude for each ratio is displayed according to the Y-axis.

3.2. *Later distance effect at the P2p for Basque pairs in the LL_S^{math}*

Distance effects at the P2p (210–250 msec) were found for Basque pairs in the LL_S^{math} group at posterior electrodes ($F_{1,8} = 5.34$, $p = .05$) (Fig. 4). This increased positivity for close distances appeared in the ascending portion of the P2 with the same posterior distribution and latency as the previously reported P2p for symbolic and non-symbolic distance effects (Libertus et al., 2007). For Basque pairs, the LL_B^{math} group showed a continuation of the previous distance effect at this latency ($F_{1,8} = 23.36$, $p = .001$; anterior electrodes in Fig. 2 and posterior electrodes and voltage maps in Fig. 4 display the effect). A continuation of the previous distance effect with anterior distribution (anterior electrodes in Fig. 2 and voltage maps in Fig. 4 display the effects) was also found for Common pairs in the LL_B^{math} ($F_{1,8} = 6.68$, $p = .03$) and LL_S^{math} ($F_{1,8} = 4.94$, $p = .05$) groups with no interaction by group ($F_{1,16} = .1$, $p = .7$).

To assure that the slight differences in general language proficiency for the two languages were not modulating the reported distance effects, the influence of relative language proficiency was also verified. Regression analyses showed that relative proficiency (the BNT score of Spanish minus Basque: maximum = 11, minimum = −2, mean = 4.67, SD = 3.94) was not related to distance effects for any pair at any latency band in any group (All $R^2 < .09$ and all $p < .1$). In addition, the effect at the P2p for Basque pairs in the LL_B^{math} group was not related to relative proficiency between languages ($R^2 = .09$, $p = .4$).

3.3. *Word retrieval efficiency and the N1–P2 distance effects*

Distance effects were not explained by the self-reported relative percentage of use between Spanish and Basque (N1–P2 distance for Common pairs: $R^2 = .05$, $p = .36$; Basque pairs: $R^2 = .027$, $p = .5$; P2p distance for Common pairs: $R^2 = .02$, $p = .58$; Basque pairs: $R^2 = .11$, $p = .68$. For the LL_B^{math} group and Basque pairs: $R^2 = .14$, $p = .32$). Remarkably, the data showed the *importance of word retrieval efficiency, but only for the early N1–P2 effect.* Word retrieval performance, which was measured as the average BNT score in Basque and Spanish, was significantly correlated with N1–P2 distance effects ($R^2 = .41$, $p = .004$) (Fig. 5). The results showed that an increase in efficiency of word retrieval is related to a larger distance effect for this component. This finding highlights the

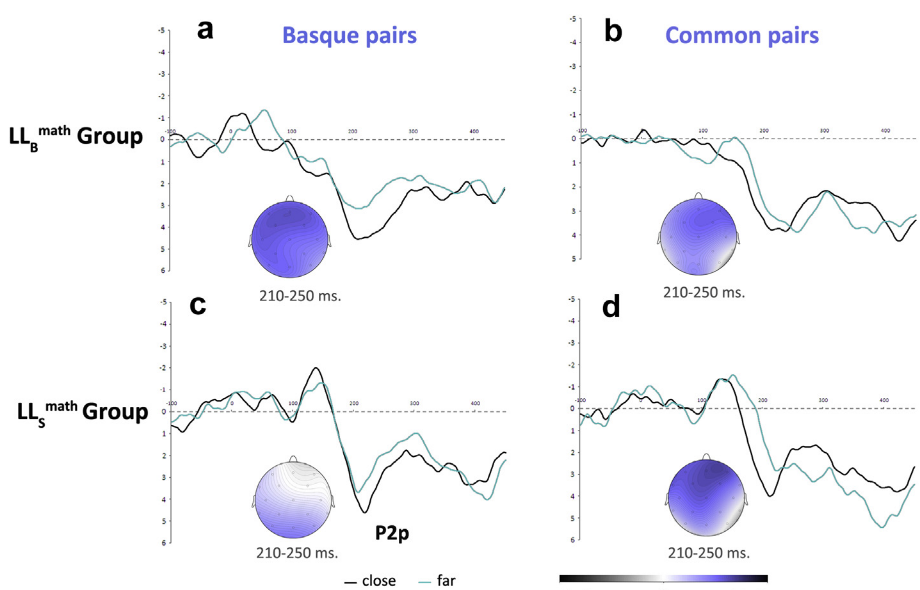

Fig. 4 – A later P2p effect for Basque pairs in the LL_S^{math} group. Only the LL_S^{math} group showed distance effects with larger amplitudes for close distances at the P2p latency and scalp distribution (b). For the rest of the conditions, there was a continuation of the previous effect at the N1–P2 (a, c, d). Pooled posterior electrodes and difference voltage maps are shown.

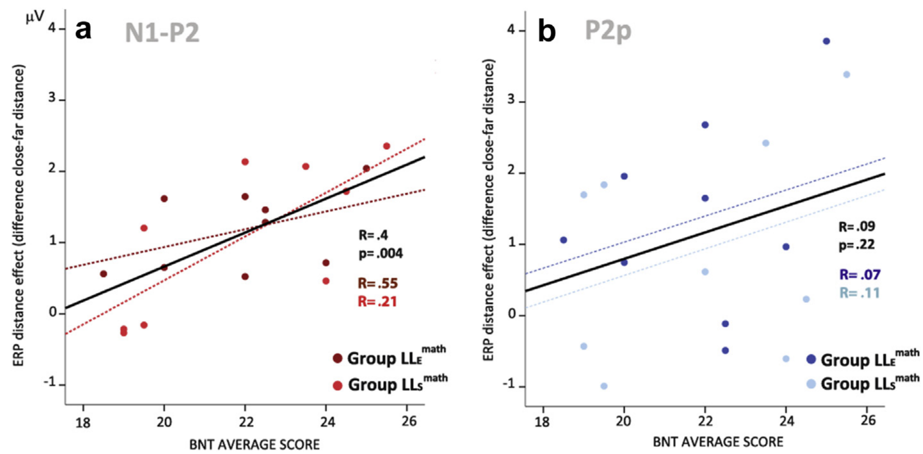

Fig. 5 – Word retrieval efficiency and distance effects. Regression analyses between BNT average score (correct responses from the 30th item) and N1–P2 (a) or P2p (b) distance effects.

importance of general linguistic ability in certain number processes and may point to an activation of the number word with the sole perception of a digit co-occurring with distance effects at the N1–P2 latency (Cao et al., 2010). Finally, word retrieval efficiency was found to be orthogonal to the P2p ($R^2 = .09$, $p = .22$; LL_S^{math}: $R^2 = .09$, $p = .41$), which clarifies the independence between language factors and the distance effect for Basque pairs found for the LL_S^{math} group.

4. Discussion

Results showed distance effects appeared at the N1–P2 latency band in both groups when Common pairs were computed (i.e., those digit pairs with a decimal link, common to Spanish and Basque). However, only the LL_B^{math} group showed an N1–P2 distance effect for the Basque pairs (i.e., those digit pairs with a Basque specific, vigesimal link). These N1–P2 effects continued with the same distribution during the P2p latency band, where a canonically posterior P2p distance effect appeared for the LL_S^{math} group while computing the vigesimal Basque pairs. On the top of this, and restricted to the described distance effects located at the N1–P2 component, distance effects were predicted by overall word retrieval efficiency as measured by averaged BNT scores. Contrarily, the P2p distance effect did not correlate with BNT scores.

The N1–P2 distance effect dissociation across groups and digit pairs suggests that number semantic properties, such as the distance effect, show some dependency with linguistic variables. This distance effect was found only for pairs grouped by the corresponding LL^{math}. Similar N1–P2 distance effects have been previously reported (Temple & Posner, 1998; Libertus et al., 2007; Cao et al., 2010; Liu, Tang, Luo, & Mai, 2011) and interpreted as an index of access to number semantics. It could be argued that N1–P2 distance effects may be due to perceptual processes of possibly retrieved number words. The parametric analysis of this effect with ratio distance values suggests that these N1–P2 modulations reflect access to quantity.

The LL_S^{math} group showed a distance effect for Basque pairs in the latency band and scalp distribution of the previously reported P2p (Temple & Posner, 1998; Libertus et al., 2007). P2p has been shown to be sensitive to numerical distance in symbolic and non-symbolic notations. All other conditions showed a carryover of the N1–P2 at this latency band. The timing and scalp distribution of this effect suggests that there is not just a delay in time but also evidence of a unique process behind this P2p effect. According to our data this later posterior effect would be independent from any linguistic information, differing from the N1–P2 component, but similar to the N1–P2 effect, it would be sensitive to quantity processing.

The fact that the two groups were equivalent in language dominance for Spanish and Basque, and differed only in their LL^{math}, demonstrates that the pattern of distance effects was determined by the specific LL^{math} of the participants. In other words, within the number domain and in balanced bilinguals, the dominant code could be plausibly determined early in childhood when symbols (LL^{math}) are associated with quantity. Future studies are necessary to determine whether a higher variability in proficiency than the low relative proficiency pattern used in the present study could modulate LL^{math} effects. Although scarce, the ideal population with which to test this would be bilinguals with a mismatch between L1 and LL^{math}. According to the profile for math functioning in our participants and the reported effects, this LL^{math} might be generally sustained into adulthood as the dominant language for math.

Finally, although word retrieval efficiency was related to quantity manipulation, no interaction between LL^{math} and pair type or main effect of pair type was found in any of the components. Thus, word retrieval efficiency association with the N1–P2 effect is the only finding that could indirectly suggest that number words are being retrieved during the comparison process. Consequently, although an activation of the number words cannot be fully discarded, the described pattern of distance effects across groups and pair types, suggests that the quantity code entails verbal traces. A quantity code with verbal traces could explain why word retrieval processes were related to number semantics in the present study.

4.1. A quantity code permeable to language?

The fact that no verbal response was asked, no verbal input was provided, and the experimental design did not vary the format of stimuli presentation suggests that the observed modulations in distance effects depend on long-term verbal traces in the quantity code, which would determine the quality of verbal signatures in quantity (Cohen Kadosh et al., 2007; Piazza et al., 2007; Cohen Kadosh et al., 2010; Cohen Kadosh et al., 2011). Only when those naming forms are integrated during early learning do we obtain early ERP distance effects.

Linguistic components in numerical representations and questions regarding a linguistic origin of numerical concepts have been extensively studied through the exact-approximate distinction (McCloskey, 1992; Dehaene & Cohen, 1995; Dehaene et al., 1999; Spelke & Tsivkin, 2001; Butterworth et al., 2008). Exact arithmetic has been shown to depend on language because it is verbally acquired by rote learning, whereas approximate or magnitude comparisons would be held independently from language through the quantity code. Specifically, the Triple Code Model (Dehaene & Cohen, 1995) for number processing incorporates language in its auditory verbal word frame, which refers to arithmetic facts or exact calculations. This model proposes that the analog magnitude representation is independent from language. A similar proposal is implied in the Abstract Code Model (McCloskey, 1992), where the abstract semantic representation operates independently from language once it is accessed. The Encoding Complex Hypothesis (Campbell & Clark, 1988) offers a more interactive view, where the analog magnitude code depends on a format based on experience, and the interaction occurs in a fundamentally modular architecture (Campbell & Epp, 2004). Nevertheless, the model does not contemplate the use of verbal information during comparison tasks with digits (Campbell & Metcalfe, 2008). Regarding the debate of whether language preludes math, studies have proposed that if true, it would only happen with exact facts and never with tasks such as approximation or comparison. It has been recently hypothesized (Dehaene, 2009) that symbols introduced in the math system may be linked to quantity in an automatic manner. In this way, Dehaene explains format dependencies on the distance effect (e.g., Cohen Kadosh et al., 2007). Our data clearly suggest that language variables in number processing are not simply restricted to exact arithmetic and that links between math and language extend to the quantity code and related tasks, with the acquisition of numerical verbal symbols.

Our proposal raises the possibility that the quantity code is permeable to language and that early linguistic prints remain in adult quantity representation. This is similar to the view that a spatial component integrates with numbers in the known mental number line (Dehaene et al., 1993; Hubbard, Piazza, Pinel, & Dehaene, 2005) or to the view that finger counting is influenced by symbolic number comparison (Domahs et al., 2012, 2010; Klein, Moeller, Willmes, Nuerk, & Domahs, 2011), which is another consequence of the apparent malleability of core number semantics (Dehaene et al., 1993; Von Aster & Shalev, 2007) together with development. This is also most likely the same mechanism by which Arabic symbols linearize the quantity system in a recent neural network (Verguts & Fias, 2004) trained by unsupervised learning. Likely, through the concurrent codification of number words and quantity, number words from LL^{math} lead to changes in perceived quantity, and, therefore, the base-20 system may be integrated together with the base-10 system (McCloskey, 1992). In turn, modifications in the quantity system due to the base-20 wording system, leads to an increased efficiency in quantity manipulation. It is possible that representational changes may relate certain quantities through links based on the vigesimal system (i.e., a link between 56 and 40 would be established for a bilingual whose LL^{math} is Basque). When quantities become linked in the quantity code, the underlying mechanism during their contrast differs from unlinked quantities. In turn, these links are of linguistic origin, perhaps of similar nature than operand related items in arithmetic facts. The use of techniques with higher spatial resolution (i.e., MEG) could provide with an anatomo-functional description of possibly different brain networks behind the reported language sensitive N1–P2, and the P2p distance effects.

4.2. LL^{math} in bilinguals

The reported data suggest that balanced bilinguals who master both languages show very different brain responses to basic mathematical tasks depending on early learning. Importantly, the LL^{math} influence would have been expected only on exact arithmetic, such as arithmetic facts that were verbally learned (Spelke & Tsivkin, 2001), and the importance of early learning in one language (L+) for exact arithmetic memory networks has been previously demonstrated (Salillas & Wicha, 2012). This study suggests that LL^{math} also impacts the quantity code. Bilinguals have a redundancy of codes for the same numeric meaning, and, therefore, the symbol-quantity match is not unitary. Nevertheless, only one of the verbal codes seems to be deeply linked to magnitude.

In summary, the present study suggests that quantity representation is permeable to language during early learning when the numerical symbolic system is acquired and is associated with quantity. Contrary to current wisdom, this concept is supported by the detection of possible linguistic marks in distance effects when simply comparing Arabic digits. The results also stress the relevance of the linguistic environment in which a bilingual learns and uses math. The selectivity of the N1–P2 distance effect on specific verbal relationships between numbers depends on LL^{math}. In addition, the management of quantity can also operate independent of language, as reflected by a later P2p distance effect. Early distance effects are related to general word retrieval efficiency. That is, both the N1–P2 and P2p effects appear to reflect processes happening during the access to quantity, as reflected by their modulation by numerical distance. However, and attending to the present data, while the N1–P2 is sensitive to putative linguistic components in the magnitude representation, the P2p appears to be a subsequent phase in magnitude manipulation, independent from language. This finding suggests that access to magnitude involves linguistic factors that have not been contemplated in previous studies and emphasizes the interplay between math and language in the development of adult numerical representations. These findings can clearly have important consequences for bilingual math operation when more complex computations are built upon more basic processes or in dyscalculia.

Such a link between math and language has educational implications wherein a variation in the linguistic code could have consequences in knowledge representation within other systems, such as math (Gentner & Goldin-Meadow, 2003; Malt and Wolff, 2010). In turn, these questions refer to the study of possible cultural cues in the quantity code.

Acknowledgments

This research was supported by European Union Marie Curie Action Contract FP7-PEOPLE-2010-IEF program to E.S, MINECO project PSI2011-23995 to E.S., and Consolider-Ingenio 2010 CSD2008-00048 to M.C.

Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2013.12.009.

REFERENCES

Barber, H. A., Ben-Zvi, S., Bentin, S., & Kutas, M. (2011). Parafoveal perception during sentence reading? An ERP paradigm using rapid serial visual presentation (RSVP) with flankers. *Psychophysiology, 48*, 523–531.

Barnard, A., Hughes, K., Gerhardt, R. R., DiVincenti, L., Bovee, J., & Cantlon, J. (2013). Inherently analog quantity representations in olive baboons (*Papio anubis*). *Frontiers in Psychology, 4*, 253.

Bernardo, A. B. I. (2001). Asymmetric activation of number codes in bilinguals: further evidence for the encoding-complex model of number processing. *Memory and Cognition, 29*, 968–976.

Brysbaert, M., Fias, W., & Noel, M. P. (1998). The Whorfian hypothesis and numerical cognition: is "twenty-four" processed in the same way as "four-and-twenty"? *Cognition, 66*(1), 51–77.

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences, 14*(12), 534–541.

Butterworth, B., Reeve, R., Reynolds, F., & Lloyd, D. (2008). Numerical thought with and without words: evidence from indigenous Australian children. *Proceedings of the National Academy of Sciences USA, 105*(35), 13179–13184.

Campbell, J. I. D., & Clark, J. M. (1988). An Encoding-Complex view of cognitive number processing: comment on McCloskey, Sokol, and Goodman (1986). *Journal of Experimental Psychology: General, 117*, 204–214.

Campbell, J. I. D., & Metcalfe, A. W. S. (2008). Arabic digit naming speed: task context and redundance gain. *Cognition, 107*, 218–237.

Campbell, J. I. D., & Epp, L. J. (2004). An encoding-complex approach to numerical cognition in Chinese-English bilinguals. *Canadian Journal of Experimental Psychology, 58*, 229–244.

Cao, B., Li, F., & Li, H. (2010). Notation-dependent processing of numerical magnitude: electrophysiological evidence from Chinese numerals. *Biological Psychology, 83*(1), 47–55.

Chauncey, K., Grainger, J., & Holcomb, P. J. (2008). Code-switching effects in bilingual word recognition: a masked priming study with event-related potentials. *Brain and Language, 105*(3), 161–174.

Cohen Kadosh, R., Bahrami, B., Walsh, V., Butterworth, B., & Price, C. J. (2011). Specialization in the human brain: the case of numbers. *Frontiers in Human Neuroscience, 5*, 62.

Cohen Kadosh, R., Cohen Kadosh, K., Kaas, A., Henik, A., & Goebel, R. (2007). Notation-dependent and -independent representations of numbers in the parietal lobes. *Neuron, 53*(2), 307–314.

Cohen Kadosh, R., Muggleton, N., Silvanto, J., & Walsh, V. (2010). Double dissociation of format-dependent and number-specific neurons in human parietal cortex. *Cerebral Cortex, 20*, 2166–2171.

Dehaene, S. (1996). The organization of brain activations in number comparison: event-related potentials and the additive-factors method. *Journal of Cognitive Neuroscience, 8*, 47–68.

Dehaene, S. (2001). Précis of the number sense. *Mind and Language, 16*, 16–36.

Dehaene, S. (2009). Origins of mathematical intuitions. The case of arithmetic. *The Year in Cognitive Neuroscience 2009: Annals of the New York Academy of Sciences, 1156*, 232–259.

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and numerical magnitude. *Journal of Experimental Psychology: General, 122*, 371–396.

Dehaene, S., & Cohen, L. (1995). Toward an anatomical and functional model of number processing. *Mathematical Cognition, 1*(1), 83–120.

Dehaene, S., Dupoux, E., & Mehler, J. (1990). Is numerical comparison digital? Analogical and symbolic effects in two-digit number comparison. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 626–641.

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*, 487–506.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: behavioral and brain-imaging evidence. *Science, 284*, 970–974.

Domahs, F., Klein, E., Moeller, K., Nuerk, H. C., Yoon, B. C., & Willmes, K. (2012). Multimodal semantic quantity representations: further evidence from Korean sign language. *Frontiers in Cognition, 2*, 389.

Domahs, F., Moeller, K., Huber, S., Willmes, K., & Nuerk, H. C. (2010). Embodied numerosity: implicit hand-based representations influence symbolic number processing across cultures. *Cognition, 116*(2), 251–266.

Federmeier, K. D., & Kutas, M. (2002). Picture the difference: electrophysiological investigations of picture processing in the two cerebral hemispheres. *Neuropsychologia, 40*, 730–747.

Feigenson, L., Carey, S., & Spelke, E. (2002). Infants' discrimination of number vs. continuous extent. *Cognitive Psychology, 44*, 33–66.

Frenck-Mestre, C., & Vaid, J. (1993). Activation of number facts in bilinguals. *Memory and Cognition, 21*(6), 809–818.

Gelman, R., & Gallistel, C. R. (1978). *The child's understanding of number*. Cambridge, MA: Harvard University Press.

Gentner, D., & Goldin-Meadow, S. (2003). In *Language in mind: Advances in the study of language and thought*. Cambridge, MA: MIT Press.

Gordon, P. (2004). Numerical cognition without words: evidence from Amazonia. *Science, 306*(5695), 496–499.

Grabner, R. H., Saalbach, H., & Eckstein, D. (2012). Language-switching costs in bilingual mathematic learning. *Mind, Brain and Education, 6*(3), 147–155.
Hsu, Y. F., & Szücs, D. (2012). The time course of symbolic number adaptation: oscillatory EEG activity and event related potential analysis. *NeuroImage, 59*(4), 3103–3109.
Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience, 6*(6), 435–448.
Iuculano, T., Tang, J., Hall, C. V., & Butterworth, B. (2008). Core information processing deficits in developmental dyscalculia and low numeracy. *Developmental Science, 11*(5), 669–680.
Jones, S. M., & Brannon, E. M. (2012). Prosimian primates show ratio dependence in spontaneous quantity discriminations. *Frontiers in Comparative Psychology, 3*, 1–8.
Kaplan, E., Goodglass, H., & Weintraub, S. (1983). *Boston naming test*. Philadelphia: Lee and Febiger.
Klein, E., Moeller, K., Willmes, K., Nuerk, H. C., & Domahs, F. (2011). The influence of implicit hand-based representations on mental arithmetic. *Frontiers in Psychology, 2*(197).
Kretzschmar, M., Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2009). Parafoveal versus foveal N400s dissociate spreading activation from contextual fit. *NeuroReport, 20*, 1613–1618.
Libertus, M. E., Woldorff, M. G., & Brannon, E. M. (2007). Electrophysiological evidence for notation independence in numerical processing. *Behavioral and Brain Functions, 3*, 1.
Liu, C., Tang, H., Luo, Y., & Mai, X. (2011). Multi-Representation of symbolic and nonsymbolic numerical magnitude in Chinese number processing. *PLoS One, 6*(4), e19363.
Luck, S. T., & Kappenman, E. S. (2012). ERP components and selective attention. In S. T. Luck, & E. S. Kappenman (Eds.), *The Oxford handbook of event-related potential components*. Oxford University Press.
Malt, B. C., & Wolf, P. (Eds.). (2010). *Words and the mind: How words encode human experience*. Oxford University Press.
McCloskey, M. (1992). Cognitive mechanisms in numerical processing: evidence from acquired dyscalculia. *Cognition, 44*(1–2), 107–157.
Moreno, E. M., & Kutas, M. (2005). Processing semantic anomalies in two languages: an electrophysiological exploration in both languages of Spanish–English bilinguals. *Brain Research Cognitive Brain Research, 22*(2), 205–220.
Moyer, R. S., & Landauer, T. K. (1967). Time required for judgments of numerical inequality. *Nature, 215*(5109), 1519–1520.
Nieder, A., & Dehaene, S. (2009). Representation of number in the brain. *Annual Review of Neuroscience, 32*, 185–208.
Nuerk, H. C., Weger, U., & Willmes, K. (2005). Language effects in magnitude comparison: small, but not irrelevant. *Brain and Language, 92*(3), 262–277.
Paulsen, D. J., & Neville, H. J. (2008). The processing of non-symbolic numerical magnitudes as indexed by ERPs. *Neuropsychologia, 46*, 2532–2544.
Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences, 14*(12), 542–551.
Piazza, M., Pinel, P., Le Bihan, D., & Dehaene, S. A. (2007). Magnitude code common to numerosities and number symbols in human intraparietal cortex. *Neuron, 53*(2), 293–305.
Pica, P., Lemer, C., Izard, V., & Dehaene, S. (2004). Exact and approximate arithmetic in an Amazonian indigene group. *Science, 306*(5695), 499–503.
Pixner, S., Moeller, K., Hermanova, V., Nuerk, H. C., & Kaufmann, L. (2011). Whorf reloaded: language effects on nonverbal number processing in first grade-A trilingual study. *Journal of Experimental Child Psychology, 108*(2), 371–382.
Rusconi, E., Galfano, G., & Job, R. (2007). Bilingualism and cognitive arithmetic. In *Cognitive aspects of bilingualism, Part1* (pp. 153–174).
Salillas, E., & Wicha, N. Y. Y. (2012). Early learning shapes the memory networks for arithmetic: evidence from brain potentials in bilinguals. *Psychological Science, 23*(7), 745–755.
Seron, X., & Fayol, F. (1994). Number transcoding in children: a functional analysis. *British Journal of Developmental Psychology, 12*(3), 281–300.
Spelke, E. S., & Tsivkin, S. (2001). Language and number: a bilingual training study. *Cognition, 78*(1), 45–88.
Temple, E., & Posner, M. I. (1998). Brain mechanisms of quantity are similar in 5-year-old children and adults. *Proceedings of the National Academy of Sciences USA, 95*, 7836–7841.
Van Opstal, F., Gevers, W., De Moor, W., & Verguts, T. (2008). Dissecting the symbolic distance effect: comparison and priming effects in numerical and non-numerical orders. *Psychonomic Bulletin & Review, 15*, 419–425.
Venkatraman, V., Siong, S. C., Chee, M. W., & Ansari, D. (2006). Effect of language switching on arithmetic: a bilingual FMRI study. *Journal of Cognitive Neuroscience, 18*(1), 64–74.
Verguts, T., & Fias, W. (2004). Representation of number in animals and humans: a neural model. *Journal of Cognitive Neuroscience, 16*(9), 1493–1504.
Verguts, T., Fias, W., & Stevens, M. (2005). A model of exact small-number representation. *Psychonomic Bulletin & Review, 12*, 66–80.
Von Aster, M., & Shalev, R. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology, 49*, 868–873.
Whorf, B. L. (1940). Science and linguistics. *Technology Review, 42*(6), 229–231, 247–248.
Whorf, B. L. (1956). *Language, thought and reality*. In J. B. Carroll (Ed.). Cambridge, MA: MIT Press.
Wynn, K. (1990). Children's understanding of counting. *Cognition, 36*, 155–193.