Core Number Representations Are Shaped by Language.

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Abstract

Language and math have been predominantly related through verbally learned arithmetic facts. The fundamental question arises of whether early learning of math in a linguistic context shapes very basic quantity processing. The particular characteristics of Basque-Spanish bilingualism allows the study of possible cultural cues in the innate "number sense". The present study shows that the management of quantity during comparison of Arabic digits is defined by the subjects' number wording system. Event Related Potentials (ERPs) revealed that the N1-P2 distance effect in highly proficient Basque-Spanish bilinguals was critically dependent on the language in which the participants had learned math (LL^{math}). It is generally accepted that without the request for a verbal response, the number comparison process operates independently from language and that distance effects (i.e., differences in processing between close and distant magnitudes) index access to the analogue quantity code. Our data suggest that quantity representations are permeable to the number naming system. These findings also underscore the importance of early learning and suggest that LL^{math} is the optimal medium for numerical communication.

Keywords: bilingualism, math cognition, quantity code, distance effect, ERPs.

1. Introduction.

Bilingual brokers in stock exchange markets perform rapid calculations while they communicate in the main 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. Such a link between math and language also has educational implications wherein a variation in the linguistic code could have consequences in knowledge representation within other systems, such as math (Gentner and Goldin-Meadow, 2003; Malt and Wolff, 2010). In turn, these questions refer to the study of possible cultural cues in the quantity code.

There are different views regarding a possible linguistic prelude to the development of numerical representations (Butterworth et al., 2008; Dehaene et al., 1999; Gordon, 2004; Pica et al., 2004). The very restricted number-words in Brazilian Amazonian tribes have an impact on exact, but not approximate, calculations (Gordon, 2004; Pica et al., 2004). Additionally, language and numerical cognition appear to become linked in children before the initiation of formal education when they start to master counting (Gelman and Gallister, 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 approximate and exact calculations, which restricts language dependence, if any exists, to exact calculations (Frenck-Mestre and Vaid, 1993; Dehaene et al., 1999; Spelke and Tsivkin 2001; Bernardo, 2001; Campbell and Epp, 2004; Rusconi et al., 2007; Salillas and Wicha, 2012). Exact arithmetic can be related to language because arithmetic facts 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 variated the linguistic code with L1/L2 input as a variable, and has used behavioral methods (Frenck-Mestre and Vaid, 1993; Spelke and Tsivkin 2001; Bernardo, 2001; Campbell and Epp, 2004; Rusconi et al., 2007), neuroimaging (Dehaene et al., 1999; Venkatraman et al., 2006; Grabner et al., 2002) and event-related potential (ERP) methods (Salillas and 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 and 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 and Vaid, 1993; Campbell and Epp, 2004 or Rusconi et al., 2007).

Only two studies to date (Bernardo et al., 2001; Salillas and 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) has also traces of language inherited from early learning. This innate code is proposed to be abstract, and its penetrability to symbols is the topic of current advances in math cognition (Dehaene, 2009; Nieder and 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 mapping between number words and magnitude representations, opening the questions of which of those linguistic codes connect to *core* math functioning, when that code predominance is settled, and how long that predominance lasts. Given the concurrent exposure to quantity in a particular language during early learning, number representations could have been shaped by language. A core magnitude representation evolves into a spatial mental image, which demonstrates malleability associated with individual and cultural differences (Seron et al., 1992; Dehaene et al., 1993). 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. 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 et al., 2008; Butterworth, 2010). Thus a broader concept, such as the language of learning math (LL^{math}), rather than just the language of learning arithmetic, could be crucial in different aspects of math functioning and applicable beyond simple arithmetic fact retrieval.

For this study, we used Arabic digit comparison: a task considered to tap into magnitude processing and independent from language (e.g. Dehaene and Cohen, 1995, see also Dehaene et al., 2003). The effects of LL^{math} on number semantics were measured using the well documented *distance effect* (Moyer and Landauer, 1967) as a dependent measure of access to semantics. 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 and Landauer, 1967; Dehaene et al., 1990), computationally modeling (e.g.Verguts and Fias, 2004; Verguts et al., 2005; van Opstal et al., 2008) and functional magnetic resonance imaging (fMRI). The distance effect can also be captured using ERPs (Libertus et al., 2007; Paulsen and Neville, 2008; Cao et al., 2010; Chao et al., 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 N1 to P2 transition and P2p amplitudes during numerical comparison (Dehaene, 1996; Temple and 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 et al., 2007; Cohen Kadosh et al., 2010; Cohen Kadosh et al., 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.

The authors relate these effects with the access to quantity. While N1 effects were more related to sensory aspects of the stimuli, the data specifically 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 a 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 and Cohen, 1995; Piazza et al., 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 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 (Brysbaert et al., 1998), while other studies have shown than unit-decade compatibility effects vary depending on the number word naming when using Arabic digits (Nuerk et al., 2005; Pixner et al., 2011). Given the response dependencies on these word-to-math process effects, electrophysiological evidence can be especially appropriate for their study. On the other hand, the way in which these word-to-math process effects occurs in bilinguals can supply crucial information on the origins and evolution of these linguistics prints. 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 (Basque and Spanish) we investigated early linguistic prints in the quantity code. 1) If number words corresponding to LL^{math} are 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}; 2) Most importantly, if ERPs elicited by distance effects to Arabic digits related through the vigesimal system differ depending on the participants’ LL^{math}, then the LL^{math} would have left long-term traces in the semantics of numbers during early learning (i.e., there is a predominance of representation in the LL^{math}).

2. Methods.

2.1 Participants

Eighteen equally proficient Spanish-Basque bilinguals participated in this study. The average age of acquisition of L2 Basque was 1.5 y (minimum 0 y, maximum 6 y). Nine participants reported learning math in Spanish (LL_S^{math} group) and nine reported learning math in Basque (LL_B^{math} group). Aside from the LL^{math}, the groups were equivalent in proficiency: LL_S^{math} proficiency in Spanish, as measured by the Boston Naming Test (BNT) (Kaplan et al.,1983; for other uses of the BNT as a measure of proficiency see e.g., Moreno and Kutas, 2005 or Salillas and Wicha, 2012), was 54.8 (2.52) and in Basque was 48.8 (3.56) ($t = 2.29$; $p = 0.05$); for the LL_B^{math} group, BNT scores were 53.4 (2) and 50.2 (3.63) ($t = 5.6$; $p < 0.001$) for Spanish and Basque, respectively. Thus, both groups were slightly more proficient in Spanish and were equivalent in relative proficiency ($t = 1.96$, $p = 0.09$). 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 et al., 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: 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 and results (Table 1). 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 bigger number (e.g., 68) was presented first. 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. 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.

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 online 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 0.01 to 100 Hz, and sampled at a rate of 500 Hz. The output of the bioamplifiers was fed into a 32 channel 12-bit analogue-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 0.1 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 0.5 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).

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 x distance x group interaction: $F_{1,16}$= 6.3, p = 0.02). A main effect of distance was found for the LL_S^{math} group ($F_{1,8}$= 8.22, p = 0.02) although this effect was significantly dependent on the digit pair type (distance x pair interaction: $F_{1,8}$ = 9.87, p = 0.014). 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 = 0.008). This distance effect was absent in Basque pairs ($F_{1,8}$= 0.38, p = 0.5) (Figure 2). 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 < 0.001; Basque pairs: $F_{1,8}$ = 10.61, p = 0.01; Common pairs: $F_{1,8}$ = 6.68, p = 0.03). All distance effects were widely distributed across the scalp and presented anterior maxima (Figure 1). No main effect of pair or group x pair interaction was significant (Fs<1). A closer view at fractioned latency bands of 20 msec between 130 to 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=0.17 in 150 to170 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 = 0.77; Basque pairs far: 0.15; Common pair close: 0.90; Common pair far: 0.09). A significant correlation between the ratios and the reported N1-P2 distance effects was found (r=0.28, p=0.016;

R=0.28, p=0.015 with all pairs included, and r=0.37, p=0.005; R=0.34, p=0.01 excluding the Basque pairs for the LL_S^{math} group) (Figure 3). In fact, the closest ratio values marginally differed in the elicited N1-P2 amplitude ($F_{1,17}$= 3.6, p=0.07) both for the highest and the lowest ratios (interaction $F_{1,17}$ = 1.8 p=0.2 n.s.). This analysis further demonstrates that number semantics had modulated the N1-P2 amplitude (Libertus et al., 2007; Cao et al., 2010).

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 = 0.05) (Figure 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). Verbal traces thus appear to have an impact just in a first phase of quantity processing (i.e., N1-P2 distance effect). 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 = 0.001; anterior electrodes in Figure 2 and posterior electrodes and voltage maps in Figure 4 display the effect). A continuation of the previous distance effect with anterior distribution (anterior electrodes in Figure 2 and voltage maps in Figure 4 display the effects) was also found for Common pairs in the LL_B^{math} ($F_{1,8}$= 6.68, p = 0.03) and LL_S^{math} ($F_{1,8}$ = 4.94, p = 0.05) groups.

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

$R^2 < 0.09$ and all $p < 0.1$). In addition, the effect at the P2p for Basque pairs in the LL_B^{math} group was not related to relative proficiency between languages ($R^2 = 0.09$, $p = 0.4$).

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: $R^2 = 0.05$, $p = 0.36$; Basque pairs: $R^2 = 0.027$, $p = 0.5$; P2p distance for Common pairs: $R^2 = 0.02$, $p = 0.58$; Basque pairs: $R^2 = 0.11$, $p = 0.68$. For the LL_B^{math} group and Basque pairs: $R^2 = 0.14$, $p = 0.32$). 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 ($R^2 = 0.41$, $p = 0.004$) (Figure 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 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 ($R^2 = 0.09$, $p = 0.22$; LL_S^{math}: $R^2 = 0.09$, $p = 0.41$), which clarifies the independence between language factors and the distance effect for Basque pairs found for the LL_S^{math} group.

4. Discussion.

The N1-P2 distance effect dissociation across groups and digit pairs suggests that number semantic properties, such as the distance effect, are critically dependent on 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 as an index of access to number semantics (Temple and Posner, 1998; Libertus et al., 2007; Cao et al., 2010; Liu et al., 2011). 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 and 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.

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 is 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 to test this would be bilinguals with a mismatch between L1 and LL^{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.

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 and Cohen, 1995; Dehaene et al., 1999; Spelke and 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 and 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 analogue 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 and Clark, 1988) offers a more interactive view, where the analogue magnitude code depends on a format based on experience, and the interaction occurs in a fundamentally modular architecture (Campbell and Epp, 2004). Nevertheless, the model does not contemplate the use of verbal information during comparison tasks with digits (Campbell and 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 manner, 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 reside 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 et al., 2005) or to the view that finger counting is influenced by symbolic number comparison (Domahs et al., 2012; Domahs et al., 2010; Klein et al., 2011), which is another consequence of the apparent malleability of core number semantics (Dehaene et al., 1993; von Aster and 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 and 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 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. It is worth noting that French children have been found to perform erroneously when they use the base-20 system, but this difficulty disappears in adulthood (Seron and Fayol, 1994), and convergent early behavioral studies have already shown number word dependent number representations in monolinguals for languages emphasizing the base-10 system, such as Chinese (Miura and Irene, 1987; Miura et al., 1988).

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 and Tsivkin, 2001), and the importance of early learning in one language (L+) for exact arithmetic memory networks has been previously demonstrated (Salillas and 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 retrieval efficiency. 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.

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Table 1. Characteristics of the stimuli

		Ratio	Absolute Difference	log(diff)	diff(log)
Basque pairs	Close	0.77	14.8	1.16	0.14
	Far	0.15	54.8	1.70	0.78
	difference	0.62	40	0.53	0.65
Common Pairs	Close	0.90	5	0.62	0.05
	Far	0.09	50	1.65	1.08
	difference	0.81	45	1.03	1.03

Figure1

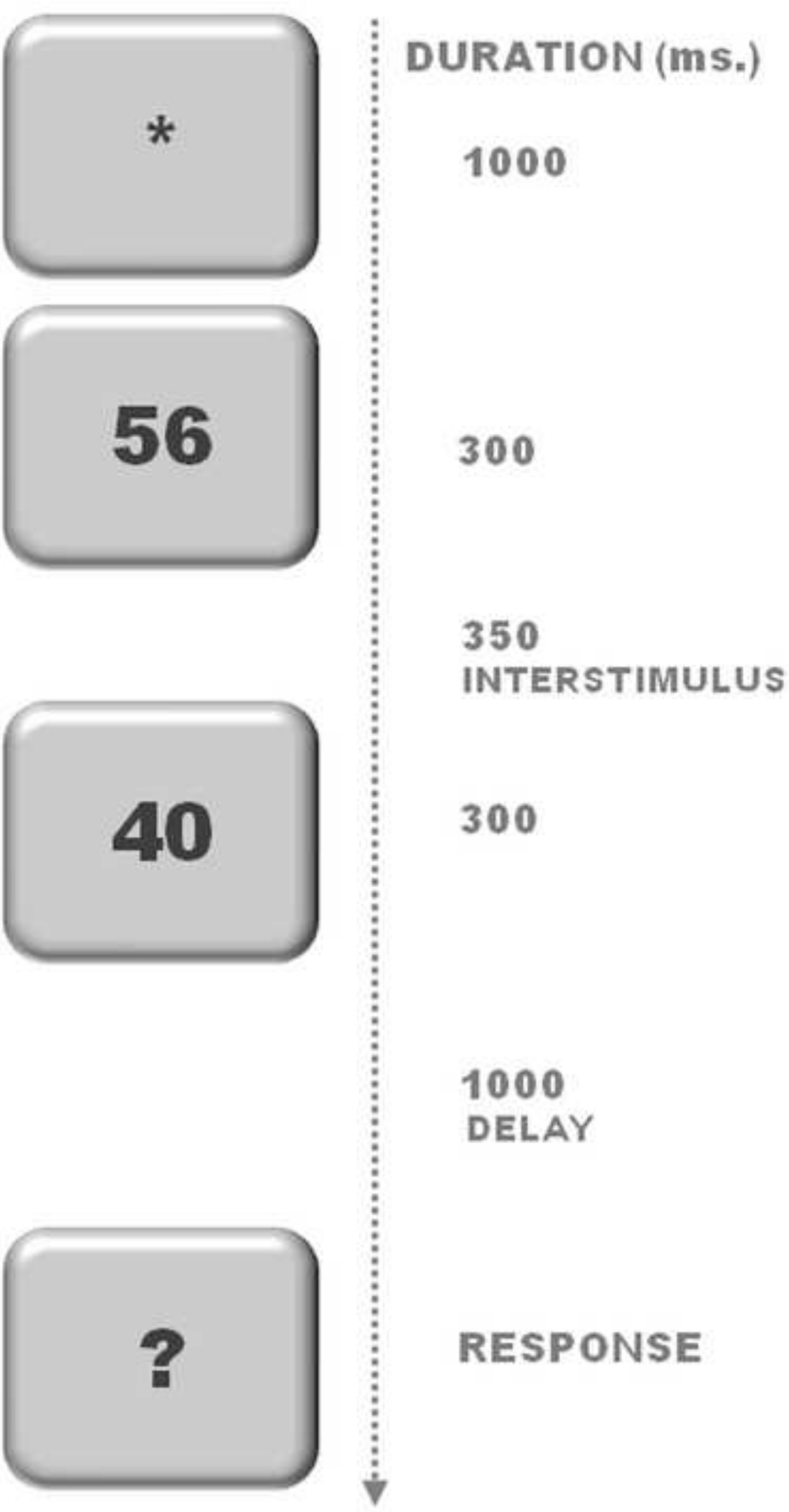
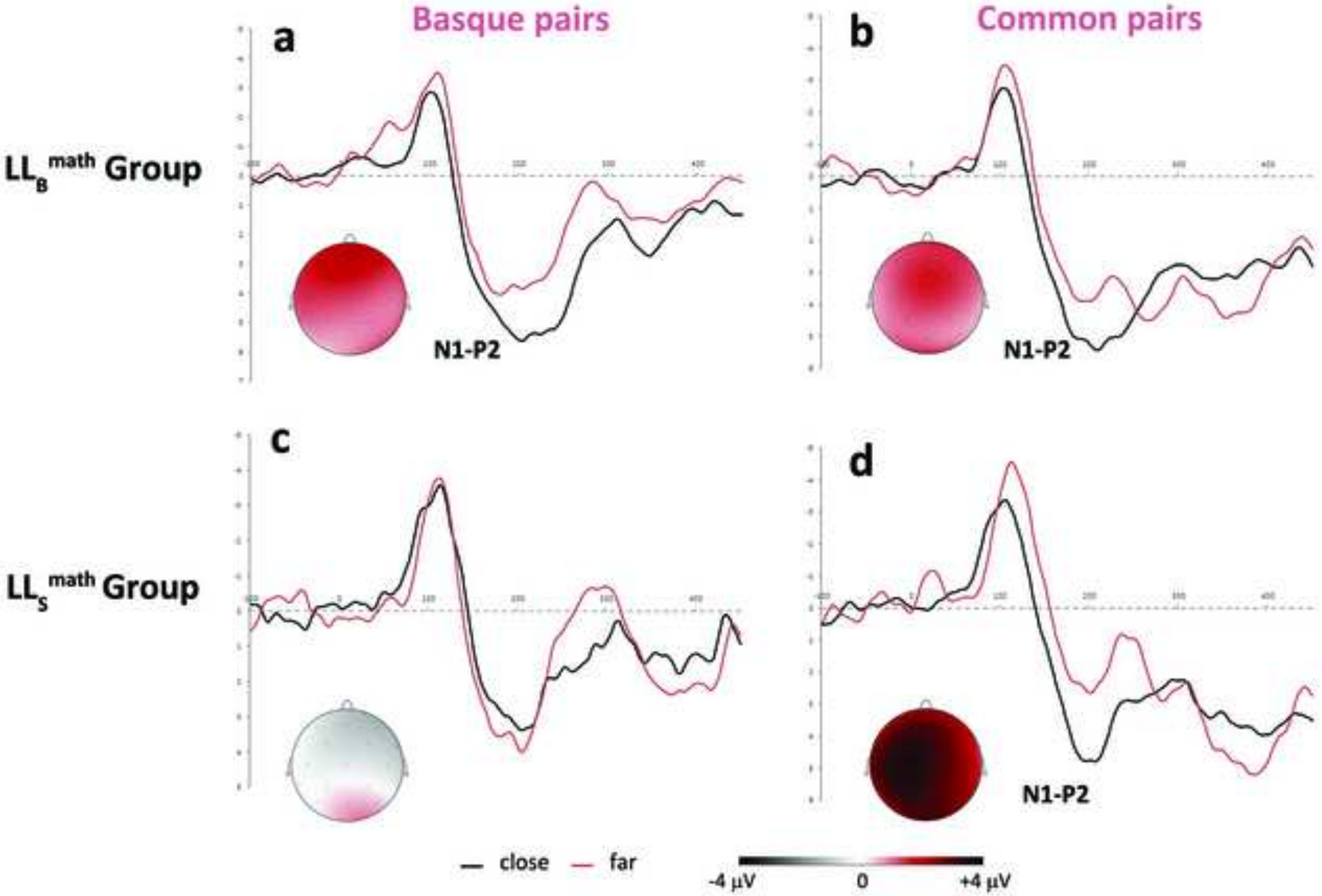

*
56
40
?
DURATION (ms.)
1000
300
350
INTERSTIMULUS
300
1000
DELAY
RESPONSE

Figure2


Basque pairs
Common pairs
a
b
c
d
LL_B math Group
LL_S math Group
N1-P2
N1-P2
N1-P2
close
far
-4 µV
0
+4 µV

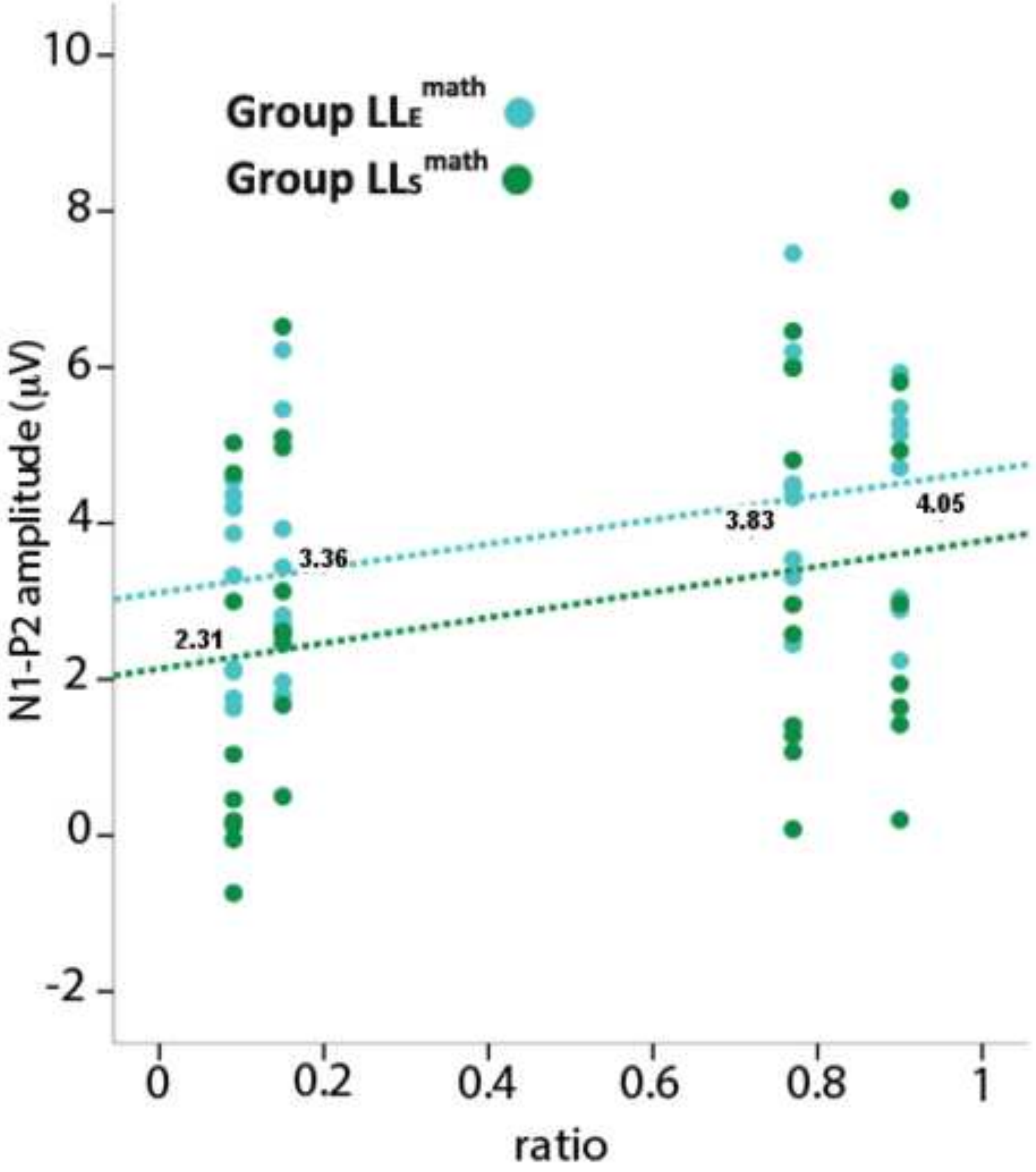

Group LL_E^{math} ●
Group LL_S^{math} ●
N1-P2 amplitude (μV)
10
8
6
4
2
0
-2
0
0.2
0.4
0.6
0.8
1
ratio
2.31
3.36
3.83
4.05

Figure4

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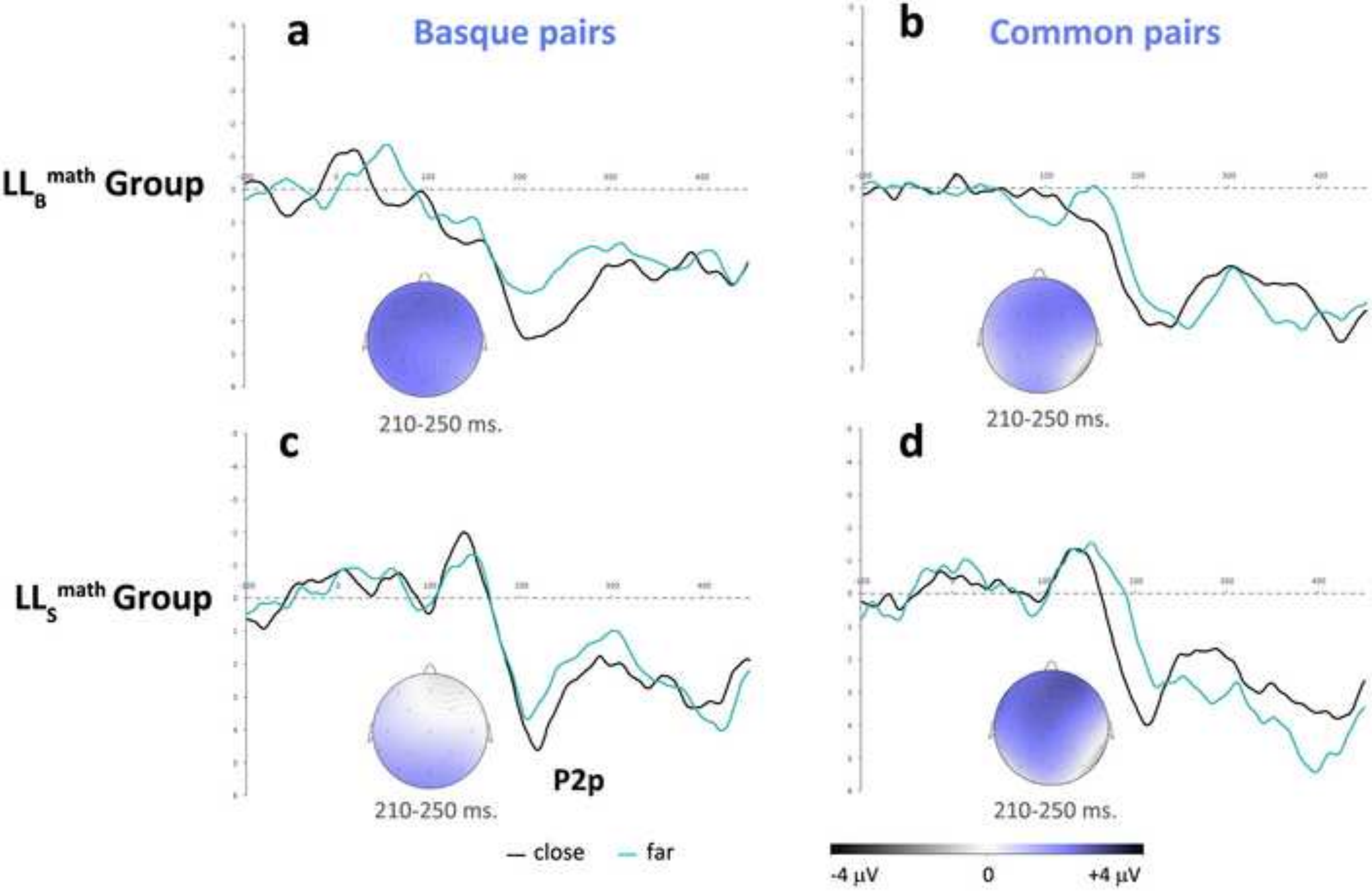

Figure5

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