1. PUBLISHABLE SUMMARY

Do language and math constitute separate areas without intersection? If they influenced each other, what would be the consequences for bilinguals? The extent to which mathematical representations and processing depend on language is a question of active debate. Some authors defend a key role of language in certain mathematical operations, such as exact arithmetic (Dehaene & Cohen, 1995; Campbell & Clark, 1998) others posit a complete independence between these two domains (Gelman and Butterworth, 2005). Bilingualism can help to elucidate this question due to the variety of number codes that a bilingual manages. Recently the researcher provided evidence on the importance of early learning in the nature of memory networks for arithmetic (i.e. exact multiplication, Salillas and Wicha, 2012). It was demonstrated that the language of learning arithmetic is what establishes the strength and quality of these networks. With the BIMATH project we took these questions forward with three main research objectives (ROs): 1) to investigate whether the language used by a bilingual has also an impact on the access to nuclear number semantics. The essential idea being that the preferred code would be the language of learning math (LL^{math}); 2) similarly, we explored whether the processing of a digit activates this verbal preferred code in a bilingual 3) importantly, the third research objective extended all these questions to developmental dyscalculia (DD). In turn, we aimed to study the impact of language in math processing through the study of bilinguals. Crucially, if we showed that in fact, language has an impact on numerical basic representations, then math in bilingualism would need attention in aspects such as the *efficiency for math* in each of the languages and by extension, the *optimization* of math communication in populations with *math difficulties and developmental dyscalculia*. In what follows we will outline the findings of BIMATH within each of its objectives. The project has also undergone extensions from its original form implying additional ways of analysis and the use of not projected techniques and populations. Due to this expansion of studies (indicated below by a letter), some of the data are under analysis at the moment of this report.

RO1: *Does the access to number semantics depend on the linguistic code used by a bilingual?* RO1 implied two experiments, with results in agreement with our hypothesis. Namely, using event related potentials (ERPs) technique we repeatedly found that the Language for learning math (LL^{math}) in bilinguals has an impact on distance and problem size effects to incremental calculation. In other words, that the LL^{math} has an impact in the access/representation of core number semantics. With **Experiment 1** (Salillas and Carreiras, in prep.) we showed that the language in which Arabic digits are simply named has an impact on their numerical distance N1-P2 effect (see Figure 1 for the results in the comparison task). Besides, this impact appears both in the context of multiplication and in the context of number comparison. The numerical or ERP N1-P2 distance effect (e.g. Moyer & Landauer, 1967; Libertus et al., 2007) is a well-known index of access to semantics. **Experiment 2** (Salillas in prep.) showed that the ERP problem size effect depends on LL^{math}. The electrophysiological response to an incremental addition of three consecutive auditory number-words with the same last number but with solutions of varying size differed depending on whether the input was LL^{math} or the other language. Specifically, ERPs to the last number showed a gradated, increasing N1 amplitude to the last digit for the other language (LL2) as a function of problem size (Figure 2). This marked gradation has been reported in the literature as associated to low math achievement (Nuñez-Peña et al, 2005).

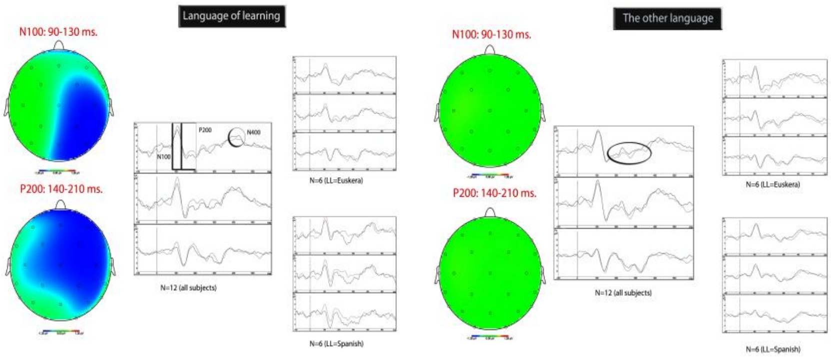

Figure 1. Experiment 1: N1-P2 distance effect only appears when pairs of numbers are named in LL^{math}

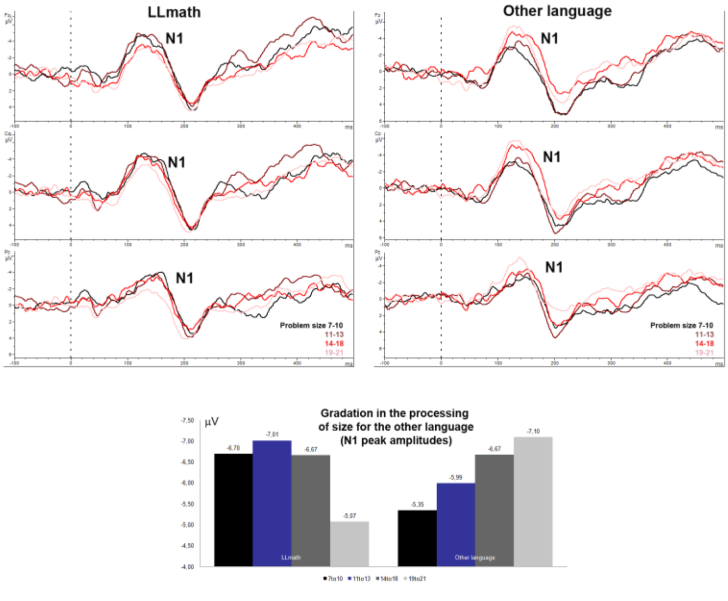

Figure 2. Experiment 2: N1 shows a clear gradation in amplitude that is dependent on the problem size effect when input is in the other language, but not in LLmath.

RO2: *Which of the bilingual's two languages is preferentially activated when an Arabic Digit is presented?* RO2 implied one experiment (**Experiment 3**, Salillas and Carreiras, under revision). The access to core number semantics (magnitude) is biased by LL^{math} in Basque-Spanish bilinguals (in convergence with Experiment 1 and RO1). Specifically, the base-20 system used in Basque for naming certain digits appeared to have a permanent trace in the number magnitude code, restricted to those bilinguals whose LL^{math} was Basque. The comparison between Arabic Digits that entailed a base-20 relationship leaded to a N1-P2 distance effect only for the group whose LL^{math} was Basque (Figure 3). This suggests that the processing of magnitude is different for these pairs and this group, as compared to base-10 pairs or the group whose LL^{math} is Spanish. Since the base 20 is only present at the linguistic level through certain number words in Basque, early learning in Basque seems to have had a long-term linguistic trace in the processing of magnitude, possibly incorporating the base-20 system. We, and other colleagues, found these results of high interest, therefore we decided to extend the paradigm to other techniques: Magnetoencephalography (MEG) (**Experiment 3b**) and analysis of EEG oscillatory activity (**Experiment 3c,** Salillas, Barraza and Carreiras, submitted). At the moment of this report, the analysis of MEG data is being performed, with the aim of finding more precise brain loci under these effects. EEG connectivity analysis shows that for the Spanish-Basque bilinguals whose LL^{math} is Basque, base 10 and base 20 system are active during the comparison of two digit numbers. Synchronization in gamma band was restricted for the base-20 pairs in the group whose LL^{math} was Basque, while base-10 pairs show synchrony in the beta band (Figure 4). A fronto-parietal network was detected which showed synchrony in the gamma band for the base-20 system that did not appear for the bilingual group whose LL^{math} was Spanish. In sum, the base-20 system for these bilinguals seems to have left a permanent trace in their quantity system.

RO3: *Implications of this data for bilingual DD.* Two experiments were performed in this part: the first (**Experiment 4**) entailed the assessment of more than 108 bilingual children with different math abilities. We were able to compare in a gradation the impact of LL^{math} in 38 of those children with higher or lower math capabilities and also between participants with low scores in basic mathematical capacities vs. low score in arithmetic. This analysis is currently in progress, still, preliminary data show, interestingly, that math scores for these children is predicted from an efficient management of number semantics through LL^{math}. On the other hand, in the last months of the project we were able to detect enough children with dyscalculia to accomplish the last of our goals. Detecting DD was a hard labour since this developmental disorder was largely unknown both by education professionals and by clinicians. After several divulgation activities and contacts with schools, some of them were recruited for a careful testing. We carried out two EEG experiments. The first experiment (**Experiment 4b**) entailed an adaptation paradigm to the different formats handled by these bilingual children. In this paradigm, a series of number words in LL^{math}, number words in the other language or Arabic digits were presented in different blocks. After an adaptation to a certain quantity, a deviant appeared with a certain distance to the adaptation value. We have observed a completely different distance effect ERP pattern for the other language in comparison to Ll^{math} or Arabic digit formats, occurring at a later time and possibly reflecting processes of translation. Another experiment (Experiment 5) explored the processing of time in these children, a topic outside of BIMATH goals. The reason to include it was that both theoretical (Walsh, 2003 vs. Dehaene and Brannon, 2011) and motivated by personal communications from parents, who reported frequent confusion with time related processes in their children.

SUMMARY AND CONCLUSIONS: The completed experiments from BIMATH suggest that a) not only exact arithmetic is susceptible of linguistic components but also core numerical representations. When electrophysiological patterns typically indexing distance effects were taken as dependent measures of quantity manipulation, these effects were qualitatively modulated by the linguistic format used as input (or output) by bilinguals; b) ERP patterns during calculation in the other language resemble those of low math achievers; c) The number wording system of LL^{math} impacts magnitude processing, as reflected by selective distance effects and by peculiar patterns of neural connectivity and oscillatory activity; d) As would be expected by these results on healthy adults, LL^{math} has, in fact, a predominant role in children with DD even for the passive management of quantity. Preliminary data also suggest that normal children with high math achievement show stronger predominance of LL^{math} in quantity manipulation. At the BCBL we will continue in the study of more precise brain loci of these effects through the MEG data analysis and with new MEG studies, since a direct comparison with EEG data is possible with MEG but not with fMRI, a technique with poor temporal resolution.

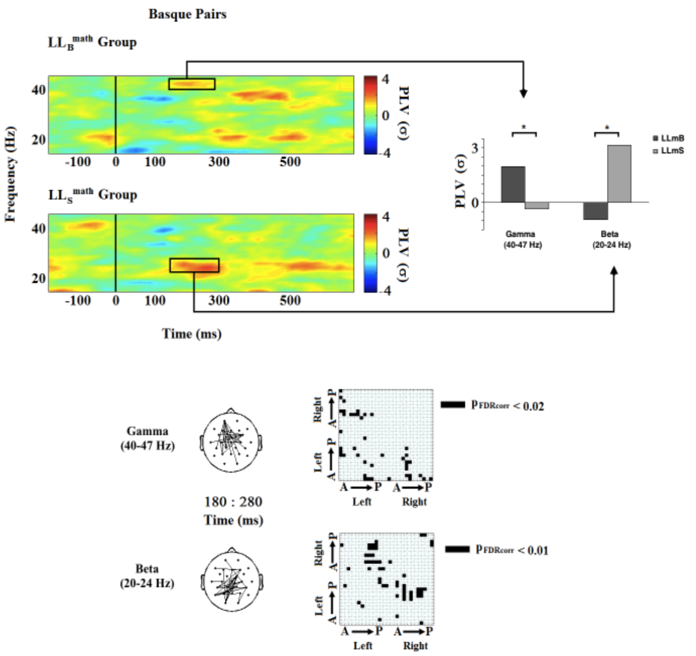

Figure 4. Experimet 3c: Connectivity analysis shows that gamma band synchronization occurs between fronto-parietal electrodes for base 20 pairs in the group of bilingual participants whose LL^{math} was Basque. The group whose LL^{math} was Spanish showed syncronization in beta band within centroparietal electrodes. The same centroparietal beta synchronization ocurred in base 10 pairs for both groups of participants.

Overall, we believe that the studies developed during this two-year project will inform the educational framework in bilingual contexts, and will help in the way of approaching bilingual dyscalculia. During the divulgation and assessment of children with DD, the special difficulties of children handling math in one of the languages was a frequent complaint from the parents and clinicians. A general understanding of how language influences math (or maybe how they influence each other) is thus of high relevance both for basic Cognitive Neuroscience and for the popular idea of a complete separation between these domains.