



# Current exposure to a second language modulates bilingual visual word recognition: An EEG study

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## ABSTRACT

Bilingual word recognition has been the focus of much empirical work, but research on potential modulating factors, such as individual differences in L2 exposure, are limited. This study represents a first attempt to determine the impact of L2-exposure on bilingual word recognition in both languages. To this end, highly fluent bilinguals were split into two groups according to their L2-exposure, and performed a semantic categorisation task while recording their behavioural responses and electro-cortical (EEG) signal. We predicted that lower L2-exposure should produce less efficient L2 word recognition processing at the behavioural level, alongside neurophysiological changes at the early pre-lexical and lexical levels, but not at a post-lexical level. Results confirmed this hypothesis in accuracy and in the N1 component of the EEG signal. Precisely, bilinguals with lower L2-exposure appeared less accurate in determining semantic relatedness when target words were presented in L2, but this condition posed no such problem for bilinguals with higher L2-exposure. Moreover, L2-exposure modulates early processes of word recognition not only in L2 but also in L1 brain activity, thus challenging a fully non-selective access account (cf. BIA + model, Dijkstra and van Heuven, 2002). We interpret our findings with reference to the frequency-lag hypothesis (Gollan et al., 2011).

## 1. Introduction

Attempts to understand how the bilingual brain adapts to deal with two linguistic registers has produced an extensive body of research. Research broadly converges on the notion that bilinguals require common brain structures for processing in both languages, but their activation depends on individual differences in proficiency level, L2 age of acquisition (AoA) and current L2-exposure (Abutalebi, 2008; Abutalebi et al., 2008; Birdsong, 2018; Perani and Abutalebi, 2005; Rossi et al., 2017). In addition, regular L2-exposure supposedly influences the control process of both bilingual languages (Grant et al., 2015) and is a key factor involved in brain plasticity (Tu et al., 2015). Yet, the potential role of L2-exposure in word recognition remains unclear. Here, we aim to elucidate how L2 language exposure modulates bilingual word recognition, given that it represents an important characteristic of the bilingual environment.

Bilingual word recognition in L1 and L2 is classically investigated via paradigms such as semantic categorisation (Boddy and Weinberg, 1981; Khateb et al., 2000, 2001, 2003, 2010; Walker and Ceci, 1985) or lexical

decision (for a review Wen and van Heuven, 2017). In semantic categorisation tasks, a prime and target are presented consecutively and participants have to answer as quickly as possible whether they are semantically related (SR) or semantically unrelated (SU). Thus, the semantic priming effects correspond to faster responses for SR than for SU words. In bilingual research, the semantic priming effect has been reproduced in bilinguals' L1 and L2, both when prime and target words were in the same language (respectively L1 and L1 or L2 and L2), and under some circumstances when they were in different languages (L1 and L2 or L2 and L1, see Altarriba and Basnight-Brown, 2007). In light of these results, a number of authors advanced that L1 and L2 share one common semantic system but with two separate lexicons (de Groot and Nas, 1991; Dufour and Kroll, 1995; Francis, 1999; Gollan and Kroll, 2001; Grainger and Beauvillain, 1988; Keatley and Gelder, 1992). However, even in highly balanced bilinguals a delayed response time for L2 versus L1 targets has been observed (Favreau and Segalowitz, 1983; Khateb et al., 2016), which stimulated the development of several cognitive bilingual models (e.g., Dijkstra and van Heuven, 2002). Yet, the role of L2-exposure in this pattern of response in highly proficient

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bilinguals is currently unexplored.

Highly influential models of bilingual word recognition, such as the Bilingual Interactive Activation Model (BIA+, [Dijkstra and van Heuven, 2002](#)), propose that words of both languages are stored in a single, shared lexicon, and that recognition is language non-selective. Yet, more recent findings suggest modulating factors, rendering bilingual lexical access more selective than originally proposed ([Casaponsa et al., 2014](#); [Casaponsa and Duñabeitia, 2016](#); [Hoversten et al., 2017](#)). Thus, the linguistic task context increases the level of language activation as a function of time performing the task, influencing performance in a top-down fashion. Models such as the BIA + do not, however, currently include factors such as individual differences in the bilinguals' environment, such as current L2-exposure, which is another potential modulator of lexical access ([Elston-Güttler et al., 2005](#)), given its known effects on language control and brain plasticity ([Grant et al., 2015](#); [Tu et al., 2015](#)), even after a short period of time (e.g., 30 days in [Tu et al., 2015](#)).

Existing data suggest fast and early effects of L2-exposure on word recognition ([Baus et al., 2013](#)). For example, [Whitford and Titone \(2012\)](#) examined the effect of L2-exposure on lexical access using eye-tracking methods. In a natural, paragraph-reading context, lexical access in L1 and L2 was indexed by the magnitude of the frequency effect on early (first fixation duration in words, in their study between 219 and 253 ms) and late oculomotor measures in reading; each of them respectively representing initial- and post-lexical processing ([Rayner, 2009](#); [Roberts and Siyanova-Chanturia, 2013](#)). The frequency effect in their study supported the assumption that low frequency words produce higher cognitive processing demands (higher fixation duration) than high frequency words. Results showed that the frequency effect was stronger in L2 than in L1 reading, but, interestingly, on early oculomotor measures, the interaction between frequency and current L2-exposure differed in either language: In L2 reading, greater L2-exposure led to a weaker L2 frequency effect, whilst in L1 reading, greater L2-exposure led to a stronger L1 frequency effect. The authors later showed similar effects emerging in parafoveal visual attention and fluency in reading ([Whitford and Titone, 2015](#)). They suggested a modulatory effect of L2-exposure on early stages of words recognition both in L1 and L2. If current L2-exposure indeed affects the earliest stages of visual word recognition, at the sublexical or lexical levels, then it appears reasonable to assume that such effects occurring during word recognition should be observable in specific event-related potential (ERP) responses, induced not only during L2 but also L1 word processing.

The electro-cortical time course of word recognition has revealed several components linked with stages of word recognition, namely the N1, the P200 and the N400 components. The N1, a negative going potential component, has been associated with contextual automatic language process such as early stages of visual word recognition ([Lee et al., 2012](#)). The P200, a positive going potential component, has been related to orthographic and phonological pre-lexical processing ([Comesaña et al., 2012](#); [Landi and Perfetti, 2007](#)), as well as to lexical access ([Coulson et al., 2005](#)). The N400 component reflects semantic processes during both sentence reading and processing isolated words (e.g., lexical decision, semantic categorisation paradigms), in which amplitude increases negatively following semantic anomalies or semantically non-matching conditions ([Khateb et al., 2010](#); [Kutas and Federmeier, 2011](#)).

In a previous study conducted on bilinguals, [Khateb et al. \(2016\)](#) used RT and ERP measures to examine the locus of the time cost difference in visual word recognition for L1 vs. L2. German–French bilinguals performed a semantic categorisation task, in which primes and targets were presented in the same language (respectively L1 and L1 or L2 and L2), and in different languages (L1 and L2 or L2 and L1). Behavioural data showed language (lexical) and semantic relatedness effects. Spatio-temporal analysis of ERP map series enabled us to identify a condition-specific ERP map series time segment (referred to as an ERP microstate) for the semantic effect (during the N400 component)

and another for the target language effect (at 170 ms, covering the P200 component). Interestingly, the ERP map segment for the target language effect was not only shorter in L1 than in L2, its duration also correlated with RTs. In addition, source localisation analysis linked this ERP time segment to the involvement of occipito-temporal regions (bilateral) including the fusiform visual word form area ([Khateb et al., 2016](#)). Thus, the electrophysiological and behavioural data reviewed so far led us to postulate that the current L2-exposure effect should be observed at the N1 and eventually at the P200 components of both languages but not necessarily at the N400 component.

In the current study, we aimed to (a) replicate and extend the findings reported by [Khateb et al. \(2016\)](#), using an identical task and methodology, and (b) examine the specific effect of L2-exposure on bilingual visual word recognition. To this end, highly balanced and proficient bilinguals were split into two groups according to their current L2-exposure (higher and lower). We could also examine whether the impact of current L2-exposure on word recognition was observable across languages or restricted only to L2. We made specific predictions for the effect of L2-exposure on behavioural neurocognitive processes.

At a behavioural level, we expected that an increase in L2-exposure would increase the basic activation level for processing L2 stimuli, with faster L2 word processing in higher L2-exposed bilinguals than in lower L2-exposed bilinguals. At the electrophysiological level, we expected that bilinguals with more L2-exposure would present early differences in word recognition processing, at the N1 and P200 (respectively indexing sublexical and lexical processes) but not at the level of the N400 (indexing semantic processes). Alternatively, in the unforeseen event that increased L2-exposure facilitates semantic access, then higher L2-exposure would modulate the N400 component. We further predicted that in the case of these highly proficient bilinguals, higher L2-exposure should lead to greater equivalence in modulation of brain activity – in each observed component – between the L1 and the L2. Conversely, lower L2-exposed bilinguals should present a lower basic activation in their L2 compared to their L1 (consistent with the conclusions of [Whitford and Titone, 2012](#)).

## 2. Method

### 2.1. Participants

Twenty-seven students (all female) from the School of Translation and Interpreting (STI) of the University of Geneva participated in the study. Three participants were discarded due to bad EEG signal (excessive eye blinks). The twenty-four students included for analysis were all right handed (Edinburgh Inventory laterality quotient mean = 0.88, SD = 0.16, [Oldfield, 1971](#)) and had a mean age of 22.24 years (SD = 2.58). They reported no history of neurological or psychiatric disorders, and had normal or corrected-to-normal vision. They signed a written informed consent, were paid for participation, and were unaware of the purposes of the study. The study protocol was approved by the ethics committee of the Geneva University and was in accordance with the ethical standards of the Declaration of Helsinki.

#### 2.1.1. Current L2-exposure and proficiency assessment

In this study, the dominant language was considered as L1 and the second less dominant language as L2 as stated by participants (both languages were used during their studies in the STI). Participants were bilinguals with different L1-L2 pairs (respectively 6 French-German, 5 German-French, 10 French-English, and 3 German-English bilinguals) and they completed a questionnaire assessing their everyday life exposure in hours to L1 and L2 ([Wartenburger et al., 2003](#)), including media (TV and radio), family, university, friends, reading and leisure activities.

Participants' proficiency in both of their languages was high. Indeed, one of the prerequisites to enrol in the STI is to have a high L2 level of at least B2 or C1 (based on the Council of Europe for the Common European Framework of Reference for Languages, <https://www.coe.int/en/>)

web/common-european-framework-reference-languages), and to succeed in a demanding admission exam. Studies in the STI take five years, in which 14 participants were in the first, 1 in the second, 7 in the fourth and 2 in the last year of their studies. Moreover, all participants filled a questionnaire providing a self-evaluation (4 liker scale, from very proficient = 1 to not proficient = 4) of their written and oral language skills (expression and comprehension). Participants were split into two groups according to the median value of current L2-exposure (median = 2.11; range 0.29–7.79), correspondingly higher and lower L2-exposure groups. Table 1 presents the demographic data and the language level evaluation of participants in each group.

2.2. Stimuli & design

The stimuli comprised sets of 200 L1 and 200 L2 concrete and imageable nouns (French-English, French-German, German-French, and German-English words, see Appendix I). Based on Dubois’s database for semantic categories (Dubois and Poitou, 2002), for each language, half of the nouns were selected from 8 natural categories (animals, trees, fruits, insects, vegetables, birds, nature, fishes) and the other half from 6 manufactured object categories (buildings, furniture, tools, transport, utensils, clothes). Cognates between and homographs between or within languages were not included in the lists. The summated bigram frequency, neighbourhood size and word frequency (expressed in a log-transformed lexical frequency) were calculated for the words in each language using the WordGen software (Duyck et al., 2004). For the calculation of these variables across languages, WordGen software uses CELEX (Baayen et al., 1996) and Lexique (New et al., 2001) databases. The average length, summated bigram frequency, neighbourhood size and word frequency are reported in Table 2.

The stimuli were 400 word pairs comprising 200 L1 and 200 L2 nouns, each of which were repeated only once in the entire stimulus set to avoid anticipation of the target word. However, each individual word was presented once as a prime and once as a target (in different pairs) in order to avoid a position effect. Each pair was composed of two consecutively presented words, respectively named prime and target word, and were manipulated according to *Semantic relatedness*: semantically related (SR) or unrelated (SU), and *Language mix*: intra-language condition, respectively L1-L1 vs. L2-L2) or in different languages (cross-language condition, respectively L1-L2 vs. L2-L1). The design therefore included eight experimental conditions each containing 50 items.

Table 1 Demographic, current L2-exposure and proficiency data (mean (SD)) between Higher and Lower L2-exposure groups.

	L2-exposure groups		p
	Higher	Lower	
N	12	12	
Age	23.09 (2.61)	21.40 (2.35)	0.109.
Laterality index	0.86 (0.20)	0.91 (0.13)	0.501.
STI year	2.38 (1.67)	2.04 (1.57)	0.6019
<b>Dominant language (L1)</b>			
AoA	5.83 (1.70)	7.00 (1.81)	0.117
Oral under.	1.00 (0.00)	1.00 (0.00)	-
Written under.	1.00 (0.00)	1.00 (0.00)	-
Oral express.	1.00 (0.00)	1.00 (0.00)	-
Written express.	1.00 (0.00)	1.08 (0.29)	0.328
Daily exposure	6.40 (3.96)	6.95 (3.30)	0.719
<b>Less dominant Language (L2)</b>			
AoA	10.50 (2.88)	12.00 (3.05)	0.228
Oral under.	1.83 (0.58)	1.83 (0.39)	1.000
Written under.	1.75 (0.45)	1.75 (0.45)	1.000
Oral express.	1.92 (0.51)	1.92 (0.29)	1.000
Written express.	2.00 (0.43)	1.92 (0.29)	0.581
Daily exposure	4.30 (1.78)	1.30 (0.53)	<0.001

-: given zero variability inferential statistical comparison is no appropriate, AoA = age of acquisition, STI = School of Translation and Interpreting, under. = understanding score, express. = expression score.

Table 2 Mean values for the psycholinguistic factors (Length, Bigram Frequency, Neighbourhood Size and Word Frequency) of words as a function of first and second languages (L1 and L2) of bilingual language pairs of the study.

L1-L2	Length		Bigram Frequency <sup>a</sup>	
	L1	L2	L1	L2
FR-GE	6.06	5.71	14276.62	17406.22
GE-FR	5.71	6.06	17406.22	14276.62
FR-EN	6.13	5.27	14418.76	8364.13
GE-EN	5.78	5.34	17651.20	8557.66
Mean <sup>c</sup>	5.92	5.59	15938.20	12151.16
L1-L2	Neighbourhood Size		Word Frequency <sup>b</sup>	
	L1	L2	L1	L2
FR-GE	2.64	2.27	1.14	0.96
GE-FR	2.27	2.64	0.96	1.14
FR-EN	2.30	5.41	1.07	1.31
GE-EN	2.17	5.07	0.97	1.27
Mean <sup>c</sup>	2.34	3.84	1.03	1.17

<sup>a</sup> Summated Position-nonspecific Bigram Frequency.  
<sup>b</sup> Expressed in a log-transformed lexical frequency. FR: French. GE: German EN: English.  
<sup>c</sup> At a level of .05 there is no significant difference between L1 and L2 means of measures.

2.3. Apparatus

The experiment was conducted on a secondary screen (with a refresh rate of 70 Hz), in an isolated electrically shielded room, using the E-Prime software (Psychology Software Tools, Inc www.pstnet.com/PA, USA). Participants were seated 130 cm from the screen, where words corresponded to a visual field between 2.78° and 6.6° of length and 0.66° of high. The electroencephalogram (EEG) continuously recorded 256 channel system (Geodesic, Inc., Oregon, U.S.A) but only 204 electrodes were included for this study. The 52 excluded electrodes were situated at the extremity of the cap and were not necessary for the purpose of the present study. A band-pass filtered between 0.1 and 200 Hz was used, impedances were kept below 20 kΩ, and the sampling rate was of 500 Hz. The EEG data were analysed off-line using the Cartool software© for EEG and ERP analysis (version 3.55 (3490); https://sites.google.com/site/cartoolcommunity/), STEN software developed by Jean-François Knebel and Michael Notter (http://doi.org/10.5281/zenodo.1164038) and RAGU toolbox ((Koenig et al., 2011) running on MATLAB (MathWorks, http://www.mathworks.com, MA).

2.4. Procedure

Before starting the experiment, participants were instructed about the task and had a training session with 15 mixed semantically related (SR) and semantically unrelated (SU) pairs (not included in the experimental task). After presentation of a word pair (read silently), participants’ task was to judge whether both words were semantically related or unrelated. Following presentation of the target word they responded as quickly and accurately as possible, using a binary button-press response (SR Box linked to Eprime), whether the words in each pair were SR or SU (counterbalanced between participants). The procedure was composed of four equivalent blocks of 100 pairs each (randomly presented between conditions) and the succession between blocks was balanced over participants. There was a 2 min delay between blocks. The total procedure lasted about 50 min.

Fig. 1 depicts the procedure of each trial. Each trial started with a central fixation cross (during 500 ms), followed by the prime word (during 150 ms), an inter-stimulus interval of 700 ms, the target word (lasting 150 ms), and finally by a white screen (pseudo-randomly presented for 1850, 2250, 2650, 3050 or 3450 ms). This procedure avoided the occurrence of a language switching effect during the semantic judgment. Indeed, participants stayed in bilingual mode (Grosjean,

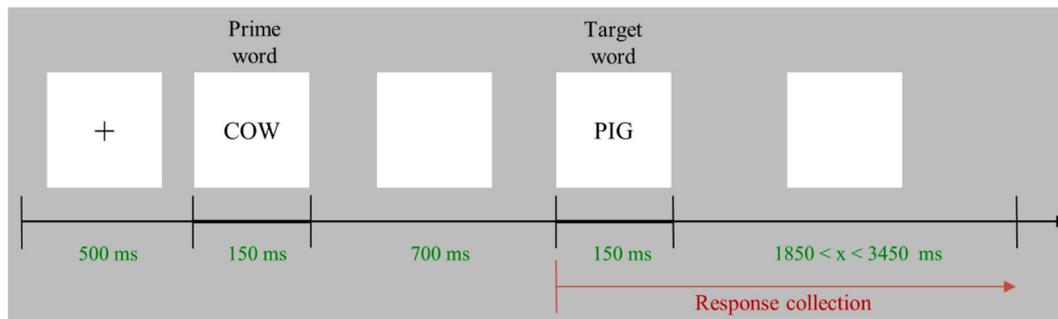


Fig. 1. **Experimental protocol:** Schematic representation of the experimental paradigm for a single trial.

1998; Ian and Bryan, 2014) after the prime because they could not anticipate the language of the target word. A similar experimental procedure to evoked an N400 effect has been used previously (Khateb et al., 2003, 2007, 2010; Küper and Heil, 2009). The words were presented in the centre of the screen, in capital letters, and without diacritics to avoid identification of language-specific bigrams (especially in German and French).

## 2.5. Behavioural analyses

The behavioural part of the present study follows a 2x2x2x2 mixed design with L2-exposure (Higher vs. Lower) as between-subjects factor, and target language (L1 vs. L2 targets), language mix (intra-vs. cross-language), and semantic relatedness (SR vs. SU words) as within-subject factors. For each participant and each experimental condition, the median reaction time (RT in milliseconds) and the percent of correct answers (accuracy) were computed. Statistical analyses were conducted using IBM® SPSS® Statistic 20. Individual RTs and accuracy rates were subjected to 2x2x2x2 mixed ANOVAs. Post-hoc analyses were performed using T-Tests with Bonferroni correction for multiple comparisons.

## 2.6. EEG analyses

### 2.6.1. EEG pre-processing

The event-related potentials (ERP) were calculated as follow: EEG epochs from correct trials were first extracted from 100 ms pre-to 800 ms post-target words onset, and baseline corrected over this whole period. Signal was band-pass filtered between 1 and 30 Hz with an additional notch filter of 50 Hz. Trials with eye-blinks or other artefacts (determined by peaks above or below 100  $\mu$ V for at least one time frame at electrode during the epoch) or with incorrect participant's response were automatically rejected. The epochs were then averaged for each participant and experimental condition separately. In the final ERP, bad electrodes (2.02%) were then interpolated using 3D spline method (Perrin et al., 1987) implemented in Cartool, and the ERP data (recorded against Cz) were recalculated against the average reference (Lehmann and Skrandies, 1980). This processing procedure has been validated in our previous work (De Pretto et al., 2021; Najberg et al., 2021; Ribordy Lambert et al., 2020).

The difference between the average number [ $\pm$  standard error of the mean (SEM)] of accepted epochs between groups and conditions was not statistically significant ( $p = .42$ ) confirming that differences in the signal-to-noise ratio did not explain the observed ERP effects (Number of accepted Epochs for higher L2-exposed; L1\_SR:  $40.4 \pm 2.24$ ; L1\_SU:  $41.0 \pm 1.96$ ; L2\_SR:  $39.0 \pm 2.2$ ; L2\_SU:  $38.5 \pm 2.60$ ; Number of accepted Epochs for lower L2-exposed; L1\_SR:  $43.9 \pm 1.46$ ; L1\_SU:  $44.3 \pm 1.29$ ; L2\_SR:  $36.8 \pm 1.17$ ; L2\_SU:  $38.3 \pm 1.35$ ).

### 2.6.2. General analytical strategy

For clarity, and to accurately test our a priori hypotheses, the EEG

analyses were computed excluding the cross-language condition. We first performed local electrode analyses at each electrode and for each time frame using an intra-language 2  $\times$  2 target language (L1 vs. L2 targets) by semantic relatedness (SR vs. SU words) within-subject ANOVA (using STEN). Local electrode analyses correspond to the canonical comparisons of voltages at local electrodes between the experimental conditions, but applied with a fully data-driven approach. We (partly) corrected for multiple tests by applying a correction for the spatial and temporal extent of significant modulations: we considered effects that manifested on at least 20% of the electrodes for a minimal period of 20 ms (Guthrie and Buchwald, 1991). This procedure was used to identify two periods of interest (POIs) to assess each of our experimental questions: POIs associated with the N1 compound for language main effect and POIs associated with the N400 compound for the semantic main effect. These POIs provided a sensitive measure where two conditions differ. However such analyses are limited in terms of their neurophysiological interpretability (De Pretto et al., 2016). Therefore, we conducted analyses of the strength and shape of electric field potentials at the scalp (described in the next section) over the signal inside of each POI. More precisely, the ERP signals inside of POIs for each participant were averaged to be reduced to a single time point in order to study the general effect of experimental condition on the corresponding EEG compound.

### 2.6.3. Global field power and global map dissimilarity analyses

The Global Field Power (GFP) and the Global Map Dissimilarity (GMD) respectively allow identifying modulations in the strength and in the configuration of the active brain network across experimental conditions (Michel and Murray, 2012; Murray et al., 2008; Tzovara et al., 2012). The GFP is calculated as the standard deviation of all electrodes voltage amplitude at a given time frame (Koenig et al., 2011; Koenig and Melie-García, 2010; Lehmann and Skrandies, 1980). A high GFP value indicates a stronger electrical field at the scalp and typically indexes highly synchronized activity of the underlying sources. The GMD is calculated as the root mean square of the difference between GFP-normalized voltage potentials across the electrode montage, and indexes changes in the scalp field topography between experimental conditions. Because a change in the electric field topography necessarily follow from a change in the configuration of the intracranial electric generators (Lehmann and Skrandies, 1980; Tzovara et al., 2012), topographic changes can be interpreted as qualitative differences in the brain network engaged between the experimental conditions. Noteworthy, because GMD is based on strength-normalized voltage potentials, the GMD and GFP measures are orthogonal and can thus be interpreted independently. A change in GFP without concomitant change in the GMD can for example be interpreted as a change in response gain between statistically indistinguishable configurations of neural generators.

GFP and GMD were analysed using robust randomization statistics (Habermann et al., 2018). The null hypothesis distribution was derived from 5000 permutations of the data (see Koenig et al., 2011) and the statistical threshold was set to  $p < .05$  (using RAGU toolbox). First, the

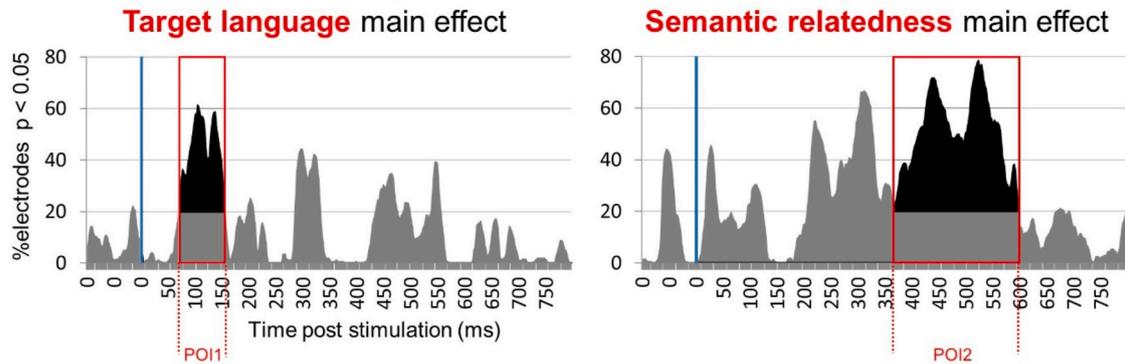


= .66), reflected faster RTs following SR (748 ms) than SU (821 ms) words (i.e. RT semantic relatedness effect). Finally, there was a significant target language by semantic relatedness interaction ( $F(1,22) = 5.276; p = .032; \eta^2 = .19$ ), showing that whilst the RT semantic relatedness effect was significant in both target language words (L1 target: SR vs. SU, 722 vs. 772,  $t(23) = -4.513; p < .001$ ; Cohen's  $d = -0.92$ ; L2 target: SR vs. SU, 775 vs. 871,  $t(23) = -5.540; p < .001$ ; Cohen's  $d = -1.11$ ), the effect was stronger in L2 than L1 target words (as supported by the effect sizes).

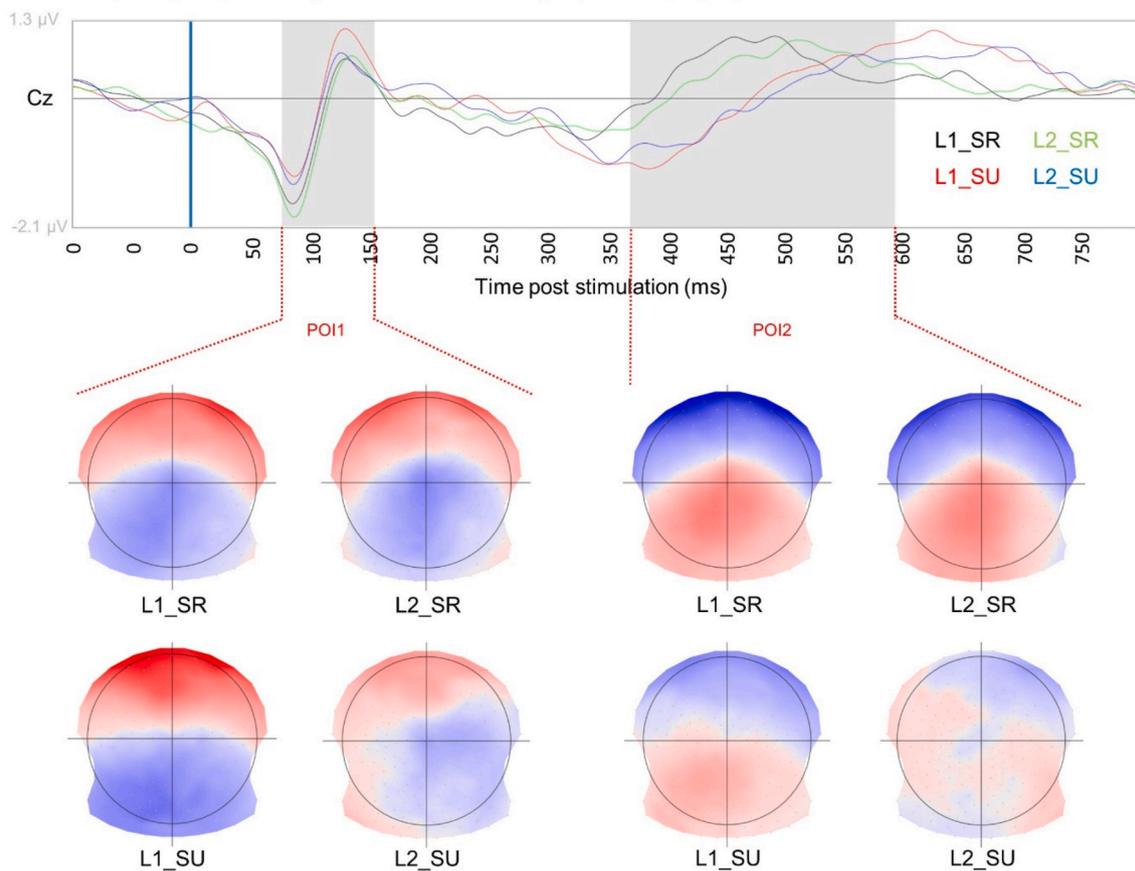
In the  $2 \times 2 \times 2$  ANOVA performed on accuracy data, a significant main effect of target language ( $F(1,22) = 46.762; p < .001; \eta^2 = .68$ ),

revealed fewer correct responses for L2 (83%) than for L1 (98%) words, whilst a significant main effect of semantic relatedness ( $F(1,22) = 6.261; p = .020; \eta^2 = .22$ ), revealed fewer correct responses for SR (89%) than for SU (92%) words (i.e. accuracy semantic relatedness effect). Finally, there was a significant target language by semantic relatedness interaction ( $F(1,22) = 4.380; p = .048; \eta^2 = .17$ ) depicting a significant accuracy semantic relatedness effect only in L2 target words (L2 target: SR vs. SU, 81 vs. 85,  $t(23) = -2.400; p = .025$ ; Cohen's  $d = -0.49$ ; L1 target: SR vs. SU, 98 vs. 98,  $t(23) = -1.187; p = .247$ ; Cohen's  $d = -0.24$ ).

A. Time- and electrode- wise analysis



B. Exemplar group-average ERP waveforms (Cz) and topographies



**Fig. 2. Electrical Neuroimaging results for the whole population.** A. Electrode-wise analyses of the ERPs to identify the POIs. The left graph shows the POI1 (Period of Interest 1) from the main effect of target language factor (L1 vs. L2). The right graph displays the POI2 from the main effect of the semantic relatedness factor (SR vs. SU). The graphs depict the percentage of electrodes showing a significant difference at each time point. B. Illustration of the waveform (grand average) for the four conditions as well as their averaged topographies inside of the POIs (L1\_SR = semantic related L1 words, L1\_SU = semantic unrelated L1 words, L2\_SR = semantic related L2 words, L2\_SU = semantic unrelated L2 words). Blue lines highlight the stimulus presentation onset and red rectangles highlight the POIs selected for further analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### 3.1.3. Cross-language condition

In the  $2 \times 2 \times 2$  ANOVA performed on RTs, a significant main effect of target language ( $F(1,22) = 31.893; p < .001; \eta^2 = .59$ ) revealed faster RTs for L1 (752 ms) than for L2 (836 ms) target words, and a significant main effect for semantic relatedness ( $F(1,22) = 8.261; p = .009; \eta^2 = .27$ ), showed faster RTs following SR (783 ms) than SU (805 ms) words (i.e. RT semantic relatedness effect). Finally, the target language by semantic relatedness interaction was marginal ( $F(1,22) = 3.065; p = .094; \eta^2 = .12$ ) and showed that the RT semantic relatedness effect was significant in L1 target words (SR vs. SU, 734 vs. 771,  $t(23) = -3.714; p < .001; Cohen's d = -0.76$ ) but not in L2 target words (SR vs. SU, 832 vs. 840,  $t(23) = -0.672; p = .508; Cohen's d = -0.14$ ).

The  $2 \times 2 \times 2$  ANOVA performed on the accuracy revealed a significant main effect of semantic relatedness ( $F(1,22) = 23.316; p < .001; \eta^2 = .52$ ) in fewer correct responses for SR (84%) than for SU (92%) words (i.e. accuracy semantic relatedness effect). No other main effects or interactions were significant.

Taken together, results from the behavioural analysis showed that both RT and accuracy data showed faster and more accurate word processing in L1 than in L2 and in SR than in SU word pairs. However, this pattern was further modulated by participants' L2-exposure: Low-

exposure bilinguals were less accurate in affirming semantic relatedness (SR vs. SU) when the target was presented in L2, whereas the same conditions presented no such loss in accuracy for high-exposure bilinguals. We elaborate on these findings, along with interesting cross-language (L1-L2 and L2-L1) effects in the discussion section.

### 3.2. EEG results

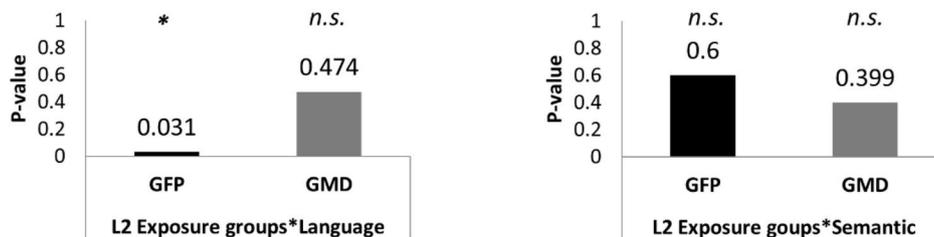
#### 3.2.1. Event related potentials

At first, explorative analysis over all ERP electrodes and time frames were conducted in order to identify POIs (Fig. 2A). This approach confirmed that the expected effects were present at the beginning, during, at the end of the specified components. Two periods met the selection criteria: a POI from 72 to 156 ms post stimulus onset (POI1) related to the target language factor (L1 vs. L2) and a POI from 366 to 596 ms post stimulus onset (POI2) associated with the semantic relatedness factor (SR vs. SU). We therefore restricted our analyses to POI1 and POI2. Fig. 2B illustrates the grand averages of the vertex electrode (Cz) for the four experimental conditions. The mean topographical map inside of each POI illustrates spatial distribution.

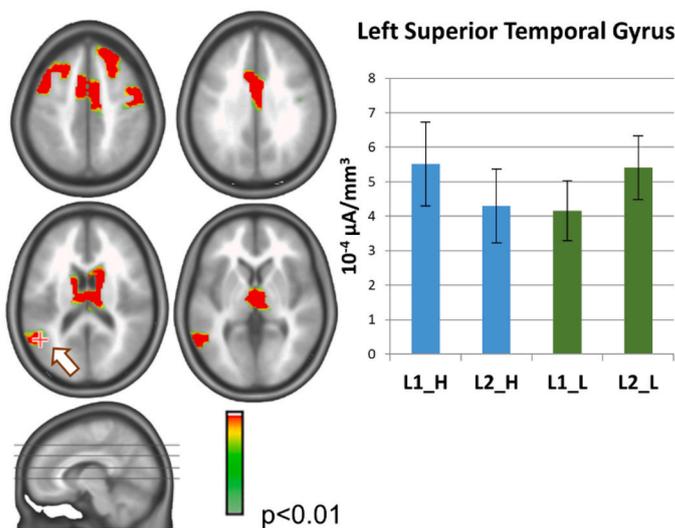
### Target language X L2 exposure interaction in POI1

### Semantic relatedness X L2 exposure interaction in POI2

#### A. P-value graphs for Amplitude (GFP) and Topography (GMD) modulation



#### B. Distributed electrical sources estimation for POI1



**Fig. 3. Electrical Neuroimaging results for the group comparison.** The left part of the figure shows the interaction between L2-exposure groups (High vs. Low) with the target language factor (L1 vs. L2) in POI1 (Period of Interest 1), and the right part of the figure shows the interaction between L2-exposure group and the semantic relatedness factor (SR vs. SU) in the POI2. (A) Results (*p-value*) of the amplitude (GFP) and the topography (GMD). \* highlights significant ( $p < .05$ ) and n. s. the non-significant results. (B) Statistical analysis of the electrical source estimations inside of the POI1 ( $p < .01; Ke = 14$ ). In the left hemisphere of the brain template, the white arrow highlights the global maxima located in the Left Superior Temporal Gyrus. The graph on the right shows the estimated peak activity of the target language (L1 and L2) by group interaction (H = Higher L2-exposed L = Lower L2-exposed). Error bars represents the standard error of the mean.

### 3.2.2. Global field power and global map dissimilarity of the periods of interests

We next checked whether the expected effects were present in the POIs. The study of GFP (amplitude) and GMD (topography) inside of previous selected periods showed significant difference of scalp field topography ( $p = .001$ ) between L1 and L2 target language inside of POI1 which is related to the N1 compound period. It was not the case for difference in amplitude ( $p = .188$ ). For the POI2 which is related to the N400 compound period, the EEG signal showed both a difference of GFP ( $p = .003$ ) and GMD ( $p < .001$ ) between semantically related and unrelated words.

Fig. 3A depicts results from the L2-exposure group interaction with each POI. In POI1 the interaction between target language and L2-exposure was statistically significant for the GFP ( $p = .031$ ) but not for the GMD ( $p = .474$ ). In POI2, no significant interaction between L2-exposure and semantic relatedness was found either for the GFP ( $p = .600$ ) or for the GMD ( $p = .399$ ). Thus, the analysis revealed a language effect in the N1 compound period and a semantic effect in the N400 compound period.

### 3.2.3. Electrical source estimation

In L2-exposure analyses (see Fig. 3B), the group analysis among individual inverse solutions showed a significant interaction between target language and L2-exposure groups in the following brain region: *cluster1* = left superior/middle/inferior temporal gyrus; *cluster2/3* = bilateral superior/middle frontal gyrus; *cluster4* = bilateral medial frontal, cingulate gyrus, thalamus; *cluster5* = right middle frontal, precentral gyrus. The global maxima was located in the left superior temporal gyrus [ $Tal = -48, -55, 17$ ]. Activities across conditions for the highest significant solution point in cluster 1 are illustrated in Fig. 3B as bar graphs. This interaction showed a decreased activation in L2 relative to L1 for the higher L2-exposure group, and the inverse pattern for the lower L2-exposure group. Notably, all the significant regions presented the same group interaction as in the global maxima. The inverse solution for the interaction between L2-exposure group factor and semantic relatedness factor inside of POI2 was not studied as no GFP or GMD result was found.

Taken together, findings from the EEG analyses show that our data revealed language effects in the N1 time course, and semantic effects in the N400 time course. A group by language interaction also emerged in the N1. Specifically, bilinguals with higher L2 exposure presented more electrical activity in the superior, middle frontal gyrus, in the medial frontal and cingulate gyrus (bilaterally), thalamus, and particularly in the Left Superior Temporal Gyrus (ISTG). The inverse activity pattern was found for bilinguals with lower L2 exposure. No group interactions were found in the N400 time course.

## 4. Discussion

The present study sought to examine how current L2-exposure affects bilingual word recognition. To this end, highly proficient bilinguals were split into higher and lower current L2-exposure groups. Participants then performed a semantic categorisation task in which primes and targets were either from the same language (i.e., intra-language: L1 – L1 | L2 – L2) or from a different language (i.e., cross-language: L1 – L2 | L2 – L1), whilst we recorded their behavioural responses and EEG signal. We predicted that bilinguals with higher L2-exposure would show behavioural and neural patterns indicative of better word recognition than bilinguals with lower L2-exposure, at an early pre-lexical and lexical levels but not at a post-lexical level. Our results in the behavioural accuracy measure and in the N1 component of the EEG signal are broadly consistent with these predictions, and suggest that L2-exposure produces early modulation of both L2 and L1 brain activity during word recognition.

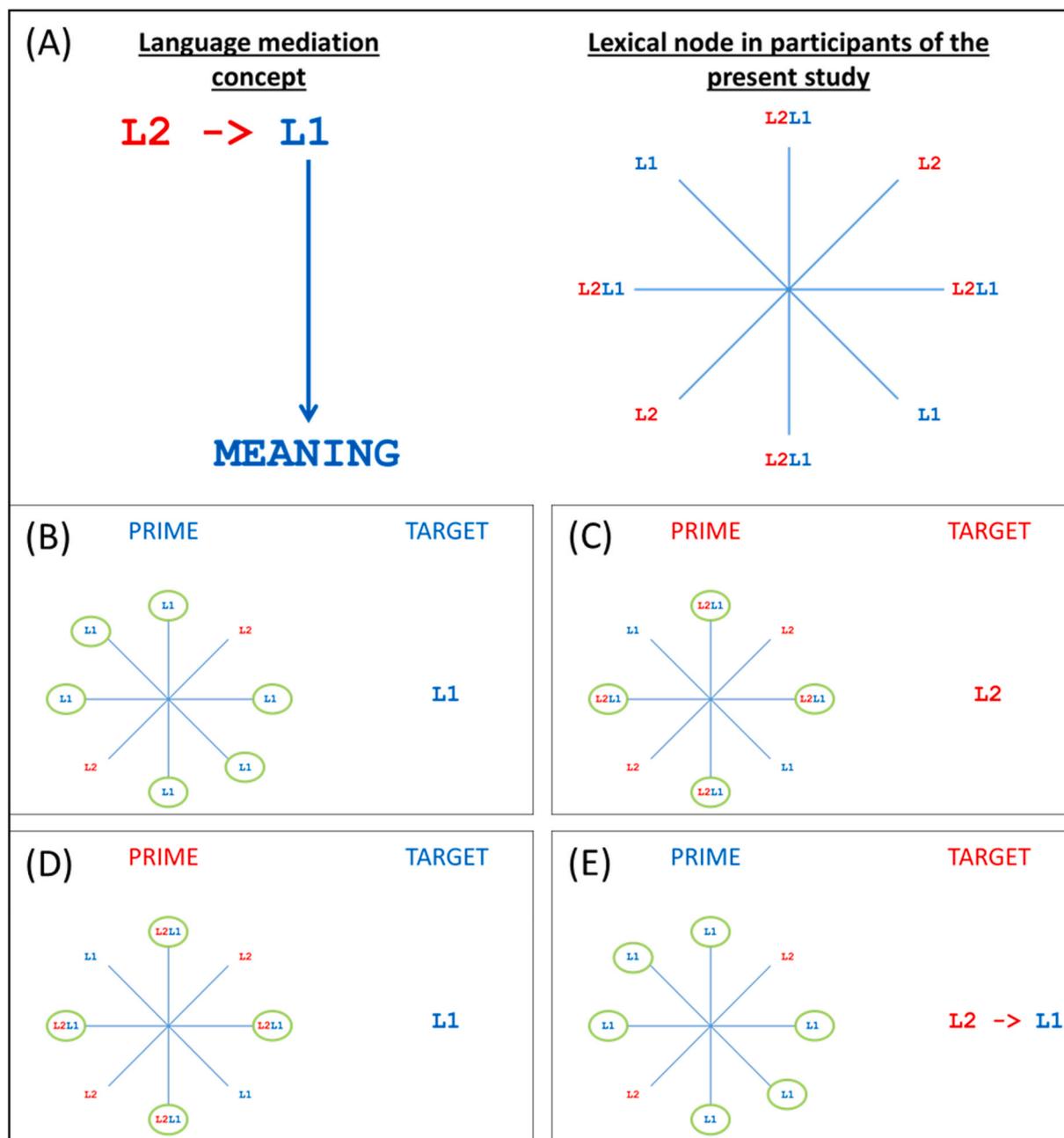
### 4.1. Behavioural findings

It is important to note item presentation in this study was fully randomised, forcing participants into a fully bilingual mode of functioning (Grosjean, 1998; Ian and Bryan, 2014). It is likely that for this reason, RTs were overall slower in this study compared with bilinguals completing the same task in a monolingual mode (as noted in Khateb et al., 2003, 2016). Both RT and accuracy data showed faster and more accurate word processing in L1 than in L2 and in SR than in SU word pairs, consistent with findings relating to language dominance in bilingualism (Puig-Mayenco et al., 2018; Rothman and Slabakova, 2018) and priming effects (Forster, 1981, 1999; Collins & Loftus, 1975; Grainger and Beauvillain, 1988). However, this pattern was further modulated by cross-language conditions and participants' L2-exposure, detailed below.

First, there was a difference between higher vs. lower L2-exposed bilinguals in the language of the target and the semantic relatedness effect. Indeed, while higher L2-exposed bilinguals did not present any difference in accuracy for target language or semantic relatedness, lower L2-exposed bilinguals presented lower accuracy in L2 than in L1 and the difference between SR and SU word pairs was significant in L2 target words only. In other words, low-exposure bilinguals are less accurate in affirming semantic relatedness when the target is presented in L2, whereas the same conditions presents no such difficulty for high-exposure bilinguals. It appears that, as exposure to a second language increases, the difference in accuracy decreases between languages and also between SR and SU word pairs. Interestingly, this suggests that the differences in accuracy between higher and lower exposure L2 bilinguals, are likely explained by an activation/inhibition mechanism rather than fewer lexical nodes in L2 than in L1 (Kroll and Stewart, 1994). Indeed, there was no interaction between the current L2-exposure and the language mix condition. Whether this benefit of current L2-exposure effect is at a pre-lexical, lexical or semantic level is the topic of the EEG section.

In the *intra-language condition* (prime and target words presented in the same language: L1-L1 and L2-L2), faster and more accurate responses were obtained in L1 than in L2, consistent with previous accounts of greater automatic access to lexical representations in L1 than in L2 (Favreau and Segalowitz, 1983). This may have been exacerbated, given that the task engendered the bilingual mode. The results also showed faster RTs for semantically related (SR) compared to semantically unrelated (SU) word pairs, consistent with classic priming effects (Collins & Loftus, 1975), in which target words from a previously activated semantic category (related prime) result in faster recognition than words from a different semantic category (unrelated prime).

Greater accuracy and faster RTs in L1-L1 trials over L2-L2 trials are also consistent with the language mediation notion of the revised hierarchical model (RHM, Kroll et al., 2010), in which L1 lexico-semantic links are direct, whereas L2 links are more likely to reference the L1 lexicon (see Fig. 4 (A), left). Precisely, the RHM states that access to L2 meaning is mediated by links from L2 to L1 lexical representations but not in the reverse direction. In addition, the RHM also specifies that L2 gains direct access to semantics with increased L2 proficiency, but which is incompatible with the sample of highly proficient bilinguals of this study: Indeed, these highly proficient bilinguals are students of translation, and are therefore more prone to continue using language mediation than regular proficient bilinguals, via the backward-dominant translation direction (e.g., L2 to L1, Mraček, 2018; Zheng et al., 2020), expanded on later in the discussion. Consistent with this framework, accuracy data obtained here showed better performance in L1 than in L2, in line with a lower number of shared lexical representations between languages (Kroll et al., 2010) than the sum of lexical representations in each language separately (because the sample contains highly proficient and balanced bilinguals, we propose an equivalent number of lexical representations in each language separately, see Fig. 4 (A), right): Assuming a language mediation account, and considering that bilinguals



**Fig. 4. Notions and cognitive schemas in priming effect postulated for the present study for both semantically related (SR) and unrelated (SU) conditions.** In (A) the left side shows the language mediation concept and on the right side the less activated shared lexical representations between bilingual languages (Kroll et al., 2010) as well as a postulated equivalent number of lexical representation in each language separately. In (B), (C), (D), and (E) we present the postulated effect of the prime word on activation of lexical representations (left side), and target words (right side) according to the study language conditions. *Intra-language* conditions are depicted in figures (B) and (C) while *cross-language* conditions are depicted in (D) and (E). Specifically, (B) depicts what is expected for a L1-L1 trial, (C) depicts what is expected for a L2-L2 trial, (D) depicts what is expected for a L2-L1 trial, and (E) depicts what is expected for a L1-L2 trial (see text for more details).

were operating in bilingual mode, L2 word pairs would prompt *activation* of equivalent L1 lexical candidates (see green circles in Fig. 4 (C)). Whereas, under this account, L1 word pairs would not similarly require such reference of equivalent L2 candidates (therefore broader activation of lexical nodes that are not restricted to the items shared with L2, see Fig. 4 (B), left section of panel).

In the *cross-language condition*, in which prime and target words were presented in different languages (L1-L2 and L2-L1), we find a different pattern, in which RTs differed according to the language of the target words. While in the L2-L1 trials the priming effect was present at the same level as in the L1-L1 trials, in the L1-L2 trials the priming effect disappeared (RTs in SR = SU, for a discussion on bilingual backward

priming see Basnight-Brown and Altarriba, 2007). However, whilst accuracy was not modulated by target word language, it was modulated by semantic relatedness: SR word pairs yielded lower accuracy than SU word pairs. Moreover, in this cross language condition SR word pairs accuracy was as low as in L2-L2 trials, while in SU word pairs the accuracy was as high as in the L1-L1 condition.

First, the finding that cross-language conditions incurred mental effort (higher RT than in intra-language conditions) and different accuracy patterns suggests a cognitive cost (Declerck et al., 2015; Kleinman and Gollan, 2018). The switching cost consists then in the effort of deactivating the lexical representations of one language to activate the lexical representations of another language (Green, 1998; Kroll et al.,

2010; Linck et al., 2008; Philipp et al., 2007; Valenti, 2013). While this effect has been observed mostly in language production (Declerck et al., 2015; Dijkstra et al., 2018), in language comprehension it has been observed only under specific language activation manipulations (Declerck and Grainger, 2017). Our data is compatible with this asymmetric switching cost in comprehension in line with a persisting reactive inhibition between languages (Philipp et al., 2007). Specifically, for SR word pairs, switching from L2 to L1 produced almost no cost, likely due to stronger automatic access. Lexical access was therefore as fast as in the L1-L1 condition. Conversely, switching from L1 to L2 produced more cost for SR word pairs, increasing processing time more than in L2-L2. For SU word pairs, cross-language trials produced an equivalent word processing time as in intra-language trials, at first glance rendering a switching cost explanation more dubious. However, even though SU RT was equivalent for L2 targets, irrespective of whether in the intra-language (L2-L2) or cross-language (L1-L2) trials, SU accuracy was different, with higher accuracy in cross-language (L1-L2) compared with intra-language (L2-L2) trials.

We consider that this pattern of results likely reflects the stronger, direct link between shared L2 lexical representations to equivalent L1 representations, that is not reciprocal in connections between L1 to L2 representations (Kroll et al., 2010), combined with the different cognitive processes involved in semantic relatedness and unrelatedness judgements. Specifically, a semantic relatedness (SR) judgement in cross-language conditions (Fig. 4, (D)), requires access to shared L1/L2 representations in order to accurately detect the semantic relationship. The presence of L2 preferentially activates shared L1/L2 representations (which is necessarily smaller in number than the sum of all representations in each language). This narrowed selection of representations then engenders lower chances of selecting a correct answer. Hence, the presence of L2 in cross-language trials engenders accuracy performance that is as low as in L2-L2 trials (Fig. 4, (C)). In contrast, a semantic unrelatedness judgement (SU) in cross-language conditions can proceed via a direct comparison of L1 lexical representations (Fig. 4, (E)), because more lexical representations are activated, increasing the likelihood of accuracy. Thus, accuracy is similar to L1-L1 trials (Fig. 4, (B)).

#### 4.2. Electrophysiological findings

Results from the electrophysiological brain activity showed target language effects between 72 and 156 ms and semantic relatedness effects between 366 and 596 ms post stimulus onset. Both respectively correspond to the N1 and N400 components in line with the Khateb et al. (2016) study. For the N1, results suggest a change in the brain networks involved between L1 or L2 target word processing. For the N400, results suggest that the semantic processing of words changes both at intracranial electric sources and their synchronization (Tzovara et al., 2012) between L1 and L2 target word processing. However, for the target language factor the P200 component was not statistically significant. The group interaction was significant in the N1 component but not in the N400 component, confirming our hypothesis of an early modulation in word recognition as a function of current L2-exposure. Specifically, results showed that the electrical potential strength differed for similar brain networks for bilinguals with higher and lower exposure to L2. The inverse solutions showed that this difference manifested in the superior, middle frontal gyrus, in the medial frontal and cingulate gyrus (bilaterally), thalamus, and particularly in the Left Superior Temporal Gyrus (ISTG). Indeed, in the ISTG (and in all the other clusters) higher L2-exposed bilinguals presented more activity in their L1 than in their L2, while lower L2-exposed bilinguals presented the inverse activity pattern. No interaction was detected at the post lexical (N400 or later) level.

In reading, the N1 component has been associated with contextual effects (Mollo et al., 2018) and automatic processing (Lee et al., 2012) at the orthographic pre-lexical level (Proverbio et al., 2002). The current findings support the notion that early effects of current L2-exposure are

located at the phonological and orthographic pre-lexical levels (Wheat et al., 2010). Source localisation analysis showed that the global maxima was situated in the ISTG including the visual word form area (VWFA in BA37, Dehaene and Cohen, 2011; Li et al., 2017; Stevens et al., 2017), giving additional support to our interpretation of a pre-lexical effect by the current L2-exposure. Indeed, a large body of work has been dedicated to the VWFA, and in reading it has been associated with a pre-lexical activation during word recognition (Brice et al., 2018; Dehaene et al., 2006), corresponding to phonological and orthographic processing. Current L2-exposure therefore modulates phonological or orthographic pre-lexical processing during word recognition. This evidence challenges the strong notion of language non-selective access advanced by the BIA + model. It suggests instead a partially selective access of both languages as stated in recent findings (Elston-Güttler et al., 2005; Hoversten et al., 2017; Hoversten and Traxler, 2016; Titone et al., 2011). In this case, L2-exposure modulates the basic activation state of both languages making one of them slightly more active over the other, assuming that language proficiency in both languages is equivalent (as in the present study).

In addition, source localisation showed significant effects in the superior, middle frontal gyrus, in the medial frontal and cingulate gyrus (bilaterally), and thalamus. These regions have been related to bilingual language control (Abutalebi et al., 2008; Branzi et al., 2016; Calabria et al., 2018) and more generally to the detection of conflicts (Correa et al., 2009; Ridderinkhof et al., 2004) as can be the case in language selection (Mouthon et al., 2019). Thus, the interaction with L2-exposure showing a decreased activation in L2 relative to L1 for higher L2-exposed bilinguals, and the inverse pattern for the lower L2-exposure group supports stronger automatic processing as a function of L2 increased exposure. In other words, when highly balanced bilinguals have to work in a less contextually activated language, they have to activate more their cingulum, as a prelude of increased inhibition of the dominant L1. This early sublexical effect may then cascade to the level of behavioural accuracy, given that higher exposure L2 bilinguals showed an advantage in detecting SR when target words were in L2.

The group interaction results in EEG are compatible with the frequency-lag hypothesis (Emmorey et al., 2013; Gollan et al., 2008, 2011), which states that dealing with two languages must be accomplished in the context of limited attentional resources, and increases in L2-exposure produce modifications in both bilingual languages at an early stage of word recognition (Whitford and Titone, 2012). This is exactly the case in the present study as the modulation of attentional resources between languages was based on the amount of L2-exposure of participants. Thus, bilinguals in the present study were highly proficient in both languages not only because of the requirements to enter into the STI, but also because they have to work directly in both languages during their studies. In this respect, our study can be considered conservative, and the impact of current L2-exposure may have been quite subtle. Indeed, future studies should include different levels between bilingual languages with a wider range of L2-exposure for elucidating the contextual impact on electrophysiological brain activity in word recognition.

#### 4.3. General remarks: limits and future research directions

The population in this study comprised highly proficient bilinguals completing a course in translation studies, of which there were different language pairs. Whilst this population can be considered a particular sub-group of bilinguals, not typically sampled for bilingual studies, it also potentially represents a new direction of research. Indeed, the pattern of responses to the task may be specific to the group of translators at several levels. Namely, the RHM states that in highly proficient bilinguals, activation of L2 words may directly access semantic information (i.e., no longer mediated by L1). However, since translators are more fluid in transitioning between their two (or more) languages they

presumably reinforce not only the L1 mediation, but also their controlled cognitive processes between languages. Importantly, the semantic relatedness task used here did not overtly require translation, and it would be necessary to investigate highly balanced non-translator bilinguals to ascertain the mental processing engaged in bilingual word recognition. Specifically, it would be important to study whether the inhibition process postulated above is restricted to translators or rather generalizable to all bilingual populations.

Another aspect concerns that the sample size in the present study is small, which incurs a risk that the effect detected could be overestimated (Button et al., 2013; Loken and Gelman, 2017). Future studies aiming to replicate the present study should include a larger sample size, that meets the criterion of 80% power (Yuan and Maxwell, 2005). In this study, the observed power of the principal three-way interaction (Semantic relatedness \* Target language \* L2 exposure) was 51%, which is just over the threshold for observed power (50%) to qualify as an adequately powered study to conclude a significant effect (Yuan and Maxwell, 2005). In order to further examine the reliability of our results, we also conducted non-parametric analyses (with Bonferroni corrections, see results in Appendix II), as advised by Bridge and Sawilowsky (1999), given that such analyses are appropriate to detect differences in small sample sizes. The pattern of results remain equivalent between the two analyses. Our conclusions concerning L2 exposure therefore remain tentative, yet they appear sufficiently robust to encourage further research on this currently understudied topic.

Finally, it is important to note that L2 exposure may overlap substantially with other influential factors such as the specific language pair of each bilingual (i.e. the L1 and L2 type) and the second language experience of each bilingual (i.e. the number of years that each participant has used their L2, calculated as the participant age minus the L2 AoA), which may impact the group results. We therefore conducted an ANCOVA with Bonferroni corrections for multiple comparisons for each factor (L1-L2 pairs and L2 experience) as covariates. In both cases, the triple interaction with group, which is of primary interest, remains significant (L1-L2 pairs:  $F(1,21) = 4.630$ ;  $p = .043$ ;  $\eta^2 = .18$ ; L2 experience:  $F(1,21) = 5.990$ ;  $p = .023$ ;  $\eta^2 = .22$ ).

## 5. Conclusion

The present study suggests that, in highly –and equivalently– proficient bilinguals, greater exposure to the second language modulates pre-lexical activation in word recognition. The electrophysiological brain activity is in line with an early L2-language exposure effect at the N1 component, while behavioural results showed only a benefit in accuracy. The findings are incompatible with the language non-selective access proposed by the BIA + model. Furthermore, a different pattern on the N1 component between bilingual languages is compatible with the frequency-lag hypothesis. While higher L2-exposed bilinguals presented higher activation in their L1 than in their L2, lower L2-exposed bilinguals presented the inverse pattern. Taken together, we tentatively suggest that higher L2-exposure bilinguals more automatically process the L2, and that this manifests at an early, pre-lexical processing stage. Future studies should replicate the findings with larger sample sizes with different language pairs.

## Author contributions

Diego de León Rodríguez: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. Michaël Mouthon: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. Jean-Marie Annoni: Conceptualization, Writing – original draft, Writing – review & editing. Assaid Khateb: Conceptualization, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors report no conflicts of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuropsychologia.2021.108109>.

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