Ultra-rapid and automatic interplay between L1 and L2 semantics in late bilinguals: EEG evidence

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Abstract

Converging behavioral and neuroimaging evidence suggests parallel activation of native (L1) and second (L2) language codes in bilinguals, with the modulation of the N400 as the most likely neural correlate of such L1-L2 interplay at lexico-semantic level. However, this relatively late effect may reflect secondary controlled processes, in contrast to earlier modulations found in monolinguals (<200 ms) indicative of fast and automatic lexico-semantic L1 access. Here, we investigated early neurophysiological crosslinguistic activation during bilingual word access. EEG signals were recorded from 17 late bilinguals during a masked-priming crosslinguistic task in which L1 (Russian) words were presented as subliminal primes for 50 ms before L2 (English) target words. Prime-target pairs matched either phonologically only, semantically only, both phonologically and semantically, or did not match. Cluster-based random permutation analyses revealed a main effect of semantic similarity at 40–60 ms over centro-posterior scalp sites, reflecting lower, more negative amplitudes for semantic similarity pairs. Importantly, neural source reconstruction showed activations within a left-hemispheric network comprising the middle and superior temporal cortex and the angular gyrus as the most likely neural substrate of this early semantic effect. Furthermore, analyses also revealed significant differences over frontocentral sites for the main effect of semantic and phonological similarity, ranging from 312–

356 and 380–444 ms respectively, thus replicating previous N400 crosslinguistic effects. Our findings confirm the existence of an integrated brain network for the bilingual lexicon and reveal the earliest (~50 ms) crosslinguistic effect reported so far, suggesting fast and automatic L1-L2 interplay.

Keywords: ERPs; semantics; bilingualism; crosslinguistic interaction; cluster-based random permutation

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1. Introduction

Increasing globalization and subsequent migration flows have transformed our world into a predominantly bilingual one (Bialystok, Craik & Luk, 2012). Despite the majority of the bilingual population learning their second language (L2) after childhood, and to a lesser extent than their native language (L1), scientific literature on cognitive underpinnings of bilingualism has traditionally focused on samples of perfectly balanced and highly proficient bilinguals; in these individuals the two languages are learned simultaneously and to a comparable degree in early life, as a consequence of upbringing in a bilingual household or, even more frequently, in a traditionally bilingual society (e.g., Bobb, Von Holzen, Mayor, Mani & Carreiras, 2020; Duñabeitia, Dimitropoulou, Uribe-Etxebarria, Laka & Carreiras, 2010; Gámez & Vasilyeva, 2020; Lallier, Acha & Carreiras, 2016). Recently, bilingual research has been shifting towards a more ecological approach and consider the more widespread case of *late*, *sequential,* and *unbalanced* bilingualism, studying bilinguals who learn their L2 after childhood (i.e., after full attainment of their L1), and to a lower degree of proficiency in comparison to L1 (e.g., Gallo, Novitskiy, Myachykov & Shtyrov, 2021; Novitskiy, Myachykov & Shtyrov, 2019; Peeters, Dijkstra & Grainger, 2013; Vega-Mendoza, West, Sorace & Bak, 2015).

In this strand of research, a long-standing question concerns the neural underpinnings of bilingualism, namely whether L1 and L2 lexico-semantic representations overlap in the bilingual brain. While early neuroimaging studies seemed to support the hypothesis of separate neural storage for L1 and L2 (e.g., Kim, Relkin, Lee & Hirsch, 1997; Perani, Abutalebi, Paulesu, Brambati, Scifo, Cappa & Fazio, 2003), more recent findings indicate that the two languages activate the same neural structures, provided that sufficient levels of L2 proficiency and exposure are achieved (Del Maschio & Abutalebi, 2018). In this sense, the level of L2 proficiency and

exposure has been systematically found to have a key role in modulating the degree of neural overlap of L1 and L2 representations in the brain. Thus, different neural activation patterns may emerge for L1 and L2 processing in low-proficient bilinguals, with L2 processing requiring recruitment of greater neural resources as compared to L1 (e.g., Marian et al., 2007; Golestani et al., 2006; Callan et al., 2003); such differences, however, tend to disappear –and the patterns of L1 and L2 activation to converge– with increasing L2 proficiency and exposure. Such findings have been reported for different types of linguistic processing, including phonology (see, for a review, Golestani, 2016), grammar (e.g., Wartenburger et al., 2003) and lexical semantics (e.g., Abutalebi, 2008). In line with the idea of shared neural representations, existing data indicates that both languages are simultaneously active in the bilingual brain during the processing of either of the two languages (for a review, see Kroll, Dussias, Bice & Perrotti, 2015).

Interactive language use is usually tested via the presentation of ambiguous linguistic stimuli to bilinguals, such as cognates (words that share meaning as well as total or partial orthography and phonology in a pair of languages), homographs (words that share orthography, but not meaning and phonology) and homophones (words that share phonology, but not meaning and orthography). The convergence in orthography, phonology, and meaning in cognates has been shown to facilitate lexical processing in bilinguals (e.g., Dijkstra & Kroll, 2005). Conversely, homographs (Durlik, Szewczyk, Muszyński & Wodniecka, 2016) and homophones (Chen, Bobb, Hoshino & Marian, 2017), which share orthographical and phonological forms but not meaning, typically elicit interference.

Not surprisingly, the methods used to investigate the neural mechanisms underlying crosslinguistic interactions in bilinguals typically include electro- and magnetoencephalography (EEG/MEG). Indeed, the main advantage of these techniques over behavioral or hemodynamic

methods is their high temporal resolution, a key feature for analyzing language processing whereby changes unfold on a millisecond scale (e.g., Beres, 2017; Shtyrov & Stroganova, 2015). To this date, crosslinguistic interplay literature has mostly focused on a particular event-related potential (ERP) component, the N400, a negative deflection peaking around 400 ms post-stimulus onset and showing a centro-parietal topographic distribution. This ERP is considered to be a highly robust brain correlate of lexico-semantic processing, sensitive to the lexical status of the stimuli and typically associated with contextual integration mechanisms (Kutas & Hillyard, 1980; Kutas & Federmeier, 2011). Both the amplitude and latency of the N400 have shown reductions during the processing of homophones (e.g., Carrasco-Ortiz, Midgley & Frenck-Mestre, 2012), homographs (e.g., Hoshino & Thierry, 2012) and cognates (e.g., Peeters et al., 2013). Such patterns are in line with classical reductions of the N400 negativity reported in monolinguals for semantically related words (Kutas & Hillyard, 1980) confirming the hypothesis about simultaneous L1/L2 neural activation during language processing. More specifically, these findings reveal the interactivity between both languages at a late lexico-semantic stage of linguistic processing, at which conceptual memory representations, shared for L1 and L2, are activated. Crucially, however, the N400 is unlikely to reflect the first-pass lexico-semantic processing or activation of word memory traces per se. Instead, considering the latency of this modulation, it is more likely to indicate controlled and post-lexical access processes taking place after the initial stages of word recognition, including, most crucially, integration of the stimulus in a wider context of the preceding sentence or other contextual information (Brown & Hagoort, 1993; Kutas & Federmeier, 2011; Holcomb, 1993). Importantly, little to no empirical evidence is available showing earlier modulation of the ERPs which could denote faster and automatic crosslinguistic interplay in the bilingual brain.

Importantly, previous EEG/MEG studies addressing brain dynamics during language processing in monolinguals have systematically found much earlier modulations of the brain signal, indicative of high speed and automaticity of lexical and semantic processes. For instance, lexical access during visual word recognition has been found to take place already at ~100 ms post-stimulus onset, as indicated by lexicality and frequency effects observed at the P1/N1 ERP complex (Hauk, Coutout & Chen, 2012; Hauk, Davis, Ford, Pulvermüller & Marslen-Wilson, 2006; Hauk, Patterson, Woollams, Watling, Pulvermüller & Rogers, 2006; Segalowitz & Zheng, 2009; Sereno, Rayner & Posner, 1998). Furthermore, evidence suggestive of semantic access taking place much earlier than 400 ms, as indexed in fast neural modulations starting between 150 and 200 ms post-stimulus onset and in some cases even earlier, around 100 ms (e.g., Davis, Libben & Segalowitz, 2019; Kim & Lai, 2012; Pulvermüller, Assadollahi, Elbert, 2001; Skrandies, 1998), has been reported by studies using various semantic manipulations such as semantic priming driven by the task context (Sereno, Brewer & O'Donnell, 2003; Segalowitz & Zheng, 2009), semantic relatedness (Hauk et al., 2006b), cloze probability (Penolazzi, Hauk & Pulvermüller, 2007) or semantic richness (Rabovsky, Sommer & Abdel Rahman, 2012). Even more impressively, other studies using paradigms with unconscious or unattended stimulus presentation (e.g., masked priming or tachistoscopic word presentation on the visual periphery, respectively) have reported effects starting around 70-100 ms (Shtyrov, Goryainova, Tugin, Ossadtchi & Shestakova, 2013; Shtyrov & MacGregor, 2016), indicating that lexico-semantic access is not only an extremely fast but to a large degree a very automatic process. These properties of high speed and automaticity of early word access are also found in the auditory domain, wherein the earliest correlates of lexico-semantic access of spoken words is known to place already from ~30-80 ms (MacGregor, Pulvermüller, van Casteren & Shtyrov, 2012;

Shtyrov, Butorina, Nikolaeva & Stroganova, 2014; Shtyrov & Lenzen, 2016), i.e., in the time interval of the earliest cortical responses to speech input, such as the P50 ERP component.

Therefore, considering these findings in monolinguals and the evidence regarding shared lexicon in bilinguals, the question is whether such early automaticity also accompanies the interplay between L1-L2. One previous ERP study (Novitskiy et al., 2019) documented a modulation trend (particularly, more negative amplitudes) around 170 ms post-target for semantically related L1-L2 word pairs in addition to the decrease of the N400 amplitude, indicating a more complex pattern of crosslinguistic interaction during word access than previously reported. Nonetheless, this earlier modulation is still relatively late compared to those found in the monolingual studies discussed above where lexico-semantic effects modulate brain signals starting from 70 ms onwards. Hence, to the best of our knowledge, the putative ultrarapid and automatic interplay between L1-L2 remains elusive, and no studies have so far provided evidence for it. Therefore, the aim of the present EEG investigation was to further examine neurophysiological instances of early L1-L2 interactivity in late bilinguals. We used a crosslinguistic masked priming design, in which primes and targets were systematically modulated for semantic and phonological consistency in a counterbalanced fashion. In order to rule out the influence of orthography, we used Russian L1 and English L2 that employ two different alphabetic scripts (Cyrillic vs. Latin), in which similar phonemes are conveyed by different graphemes; this allows disentangling phonological effects from those of purely visual word similarity. Using high-density EEG, we recorded ERPs to L2 targets following “invisible” masked L1 primes and explored crosslinguistic effects at each time point and scalp site during long segments of continuous word processing. Importantly, this data-driven, exploratory approach allows for the detection of effects across the time-course of stimulus processing,

without the pre-selection of time windows corresponding to specific ERP effects. Finally, we also explored underlying neural sources of any found effects.

We expected this methodology would allow us to detect putative crosslinguistic effects at early, pre-lexical stages of the L2 processing, indicative of the fast and automatic L1-L2 interplay in a shared lexical system and hence a high level of interactivity during L2 lexico-semantic access. In particular, we hypothesized that the presentation of L1 primes similar to L2 targets at phonological and/or semantic levels would influence and facilitate the processing of L2 words, with these similarity effects being reflected in late as well as early ERP modulations, likely showing reduced N400 amplitudes as well as more negative early deflections, according to the literature reviewed above. In contrast, if lexico-semantic access in bilinguals proves to follow a sequential rather than an interactive process even in the case of a shared lexicon, L1-L2 similarity effects would be restricted to late processing stages and thus reflected exclusively in the reduction of the N400, as found in previous crosslinguistic studies.

2. Materials and methods

Participants

Seventeen young adults (13 females; mean age 20.6±.7 years) were recruited from the student population of the HSE Department of Psychology. All participants were right-handed according to the Edinburg Handedness Inventory (Oldfield, 1971; mean score: 71.9±5.6%), had normal or corrected-to-normal vision, and reported no neurological or psychiatric disorders.

All participants were native Russian speakers with varying English L2 proficiency. As a considerable proportion of courses at HSE are delivered in English – often by English speaking tutors – all participants used both L1 and L2 daily, and their overall L2 proficiency was

relatively high. Participants' bilingual background was extensively assessed using the Language Experience and Proficiency Questionnaire (LEAP-Q, Marian, Blumenfeld, & Kaushanskaya, 2007). Participants' L2 proficiency and exposure, although being centered around medium-high values (mean self-assessed L2 proficiency = 7.5/10; mean L2 exposure = 5.1[1]), showed variability (SD for self-assessed L2 proficiency = 1.5; SD for L2 exposure = 2.7), indicating individual differences in the bilingual profiles of the sample. Similarly, variability emerged around the mean L2 age of acquisition (mean = 11.9 ± 3.5). See Table 1 for detailed information regarding participants' bilingual background. In addition, a forced choice vocabulary test was also carried out in order to obtain an objective measure of participants' L2 proficiency (see the Procedure section for details).

The study was approved by the HSE University ethics committee and participants were compensated for their participation. Data obtained and code used in this study will be made available via reasonable request to the authors, conditioned to the need for a formal data sharing agreement.

Stimuli

A total of 365 experimental stimuli, divided in five lists of 73 stimuli, were selected for the crosslinguistic masked-priming task. List 1 included Russian nouns which were matched by phonologically close English nouns in List 2 (e.g., дичь [dʲˈit͡ɕ] – ditch = game). List 3 consisted of Russian words which semantically matched to List 2 English words (e.g., ров [rɔf] – ditch = ditch), but did not share phonology. As a note, Russian words in this list were either direct translations to those in List 2 English words (e.g., ров [rɔf] – ditch = ditch) or, if they could not

[1] Since no participants reported exposure to L2 in the family context, due to the fact that no relatives spoke their L2, average L2 exposure was computed from the other four categories (see Table 1 for details).

be found, a closely related Russian word (e.g., сыр [sɨr] – snack = cheese). List 4 consisted of English words phonologically and semantically unrelated to Russian words in lists 1 and 3, with comparable frequency. List 5 consisted of Russian words formed by transliterating list 4 items in Cyrillic alphabet (the standard way of treating foreign words in Russian texts) thereby creating both phonological and semantic similarity between lists 4 and 5 (памп [pʌmp] – pump –). The use of transliterations as the best choice for constructing phonologically and semantically similar words in both languages was motivated by the following reasons. First, transliterating foreign items in Cyrillic is the only standard way of presenting foreign words in Russian language. Thus, native Russian speakers are highly familiar with English-Russian transliterations, and they are extensively exposed to them through different written language means (e.g., media, literature, advertising, etc.) as well as through a massive use of English borrowings. Moreover, processing transliterated primes can also be considered analogous to the processing of pseudo-homophones known to evoke a reduced N400 response (Briesemeister, Hofmann, Tamm, Kuchinke, Braun & Jacobs, 2009; Newman & Connolly, 2004). In this sense, transliterations are a better choice than cognates, considering that many cognate words deviate phonetically between languages, thus leading to substantial differences in their pronunciation. Therefore, since transliterations are effectively borrowed words resembling an English word used in Russian context, they appear to be an appropriate and transparent manner of creating linguistic materials that share both phonological and semantic features. Finally, another 365 items were selected as fillers. These fillers were monosyllabic words and pseudowords, making 5 additional lists, matched with the experimental lists in lexical frequency and length. List 6 comprised the English translations of the Russian words from the List 1. List 7 was a collection of non-related Russian words matched in frequency with List 1. List 8 included the transliterations of the List 7 into Latin script.

Components in List 10 were English pseudowords made up from the recombination of the initial and final phonemes of the Lists 2 and 4. List 10 included the Russian transliterations of the List 9, i.e., also pseudowords. The fillers were grouped into 3 conditions with Russian primes and English targets, similarly to the experimental conditions. Filler condition I combined lists 1 and 6, filler condition II combined lists 7 and 8, while filler condition III combined lists 9 and 10. Therefore, all experimental words and fillers were monosyllabic and did not differ in their lemma frequency between the lists, as confirmed by paired t-test comparisons. The lemma frequency of English and Russian words was taken from the COCA online database (http://corpus.byu.edu/coca) and the online Sharov corpus (http://www.artint.ru/projects/frqlist.php), respectively. All stimuli are presented in Appendix A.

Table 1. LEAP-Q results

	Russian		English	
	Mean	**SD**	**Mean**	**SD**
Critical age (years)				
Start speaking	0.7	1.26	8.5	3.08
Fluent speaker	5.1	2.93	14.5	3.66
Start reading	5.2	1.01	10.8	3.09
Fluent reader	7.3	2.33	13.9	4.02
Language environment (years)				
Country	18.9	5.41	0.8	1.46
Family	20.3	2.47	0	0.03
School/work	17.1	3.19	3	4.13
Proficiency (0–10)				
Speaking	9.9	0.24	7	1.5
Understanding	10	0	7.6	1.45
Writing	10	0	7.8	1.6
Contributing factors (0–10)				
Friends	8.3	2.05	4.6	3.61
Family	9.6	0.86	0.5	1.94
Reading	9.2	0.88	8.1	1.78
TV	7.1	2.78	4.1	3.21
Music	6.8	2.86	6.5	2.35
Exposure (0–10)				
Friends	9.4	0.88	2.8	2.33
Family	9.7	0.85	0	0
Reading	8.4	1.84	7.3	2.02
TV	6.1	4.2	3.1	3.45
Music	6.3	3.27	7	2.87
Accent (0–10)				
Self estimate	1.2	2.3	5.5	2.65
Others' estimate	0.8	2.02	8.1	2.74

Procedure

Participants were seated in an electrically shielded and soundproof room. First, they were administered behavioral tests for handedness (Edinburg Inventory) and language background assessment (LEAP-Q); after the necessary preparation for EEG recording (see below for details)

they were introduced to the crosslinguistic masked-priming task. Stimuli were visually displayed on a computer screen by means of the Presentation v18.1 software (Neurobehavioural Systems Inc, www.neurobs.com). The sequence of presentation was as follows. First, a fixation cross was displayed for 1050–1550 ms, randomly jittered in 100-ms steps. Then a 500-ms forward mask of percent symbols (%) was presented, followed by a 50-ms prime. Then the target stimulus was presented for 500 ms, followed by a final mask of percent symbols displayed for 50 ms (see Figure 1). Note that the same 500-ms forward mask was presented across all conditions, thus avoiding potential differences in the visual processing of primes that could confound our results. In addition, 20 % of trials were followed by a 1000 ms catch word intended to ensure the participant's attention. Catch trials were randomly presented along the task after a 1000-ms delay, half of them consisting of target repetitions (match cases) and the other half of randomly chosen words (non-match cases). For these trials, participants were asked to decide whether the catch word matched the previously presented target word or not by pressing "Z" with their left hand or "M" with their right hand on a computer keyboard, respectively. Feedback was presented on the screen only if the response was incorrect or was too slow. Trials with no response within 1000 ms after catch presentation were excluded from analysis. Behavioral data (response latencies and accuracy) from these catch trials were obtained for further analysis.

In order to include all possible modifications of semantic and phonological (dis)similarity, four different combination types of primes and targets (below referred to as conditions) were employed, recombining stimuli from the different lists. In the condition S-P+ (Semantics-Phonology+), the words of lists 1 and 2 were combined to ensure only a phonological, but not a semantic, similarity within each prime-target pair. Re-shuffling of the same words from the two lists to achieve no relationship, either phonological or semantic,

produced the S-P- condition (Semantics-Phonology-). Therefore, items in lists 1 and 2 were presented thrice during experiment (List 2 in S-P-, S-P+, S+P-; List 1 in S-P-, S-P+, and in one of the filler conditions) but, importantly, each every prime-target combination was unique, regardless of the condition. Semantically related word pairs from lists 3 and 2 constituted the S+P- condition (Semantics+Phonology-). Finally, the combination of lists 5 and 4 made up the S+P+ condition (Semantics+Phonology+). Therefore, all prime stimuli were Russian words or Russian-transliterated words spelled in Cyrillic script while all targets and catches were English words in Latin script. All types of trials were presented equiprobably in a pseudo-randomized fashion. Stimuli were presented in black 50-pixel font over a grey background. Primes and catches were presented in lower case, while targets were presented in upper case. Participants received a short training before starting the task, without subliminal primes and with feedback for both correct and incorrect responses. The entire task lasted about 30 min. For participants' comfort, the task was subdivided into 7 sub-blocks with a short self-timed pause between them, to reduce fatigue. After the main test phase, participants answered a questionnaire that probed the masked prime was not consciously perceived and only targets remained visible.

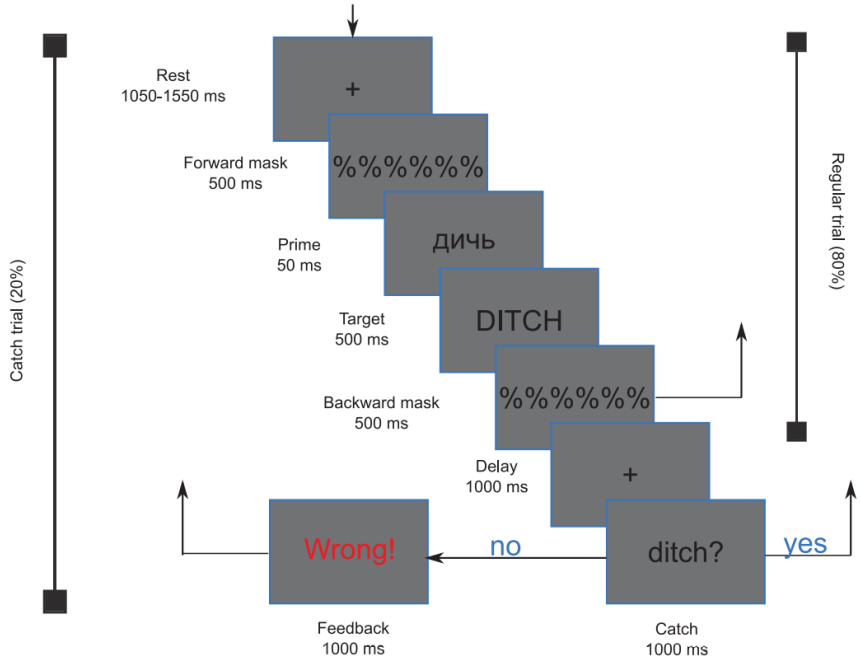

Figure 1. Experimental sequence of stimuli presentation during the crosslinguistic masked-priming task.

Finally, in order to objectively evaluate participant's proficiency in English, the 146 English words from lists 2 and 4 were presented in an unspeeded forced-choice task. Participants were asked to choose the correct translation into Russian among three given alternatives by pressing 1, 2 or 3 in the keyboard. The feedback was presented immediately for both correct and incorrect responses and participants' response accuracy was recorded. The vocabulary task was always administered after the crosslinguistic masked-priming task, to avoid its influence on the former.

Behavioral data analysis

Latency (reaction times) and accuracy (hit rates) data were measured separately for 4 conditions (S-P-, S-P+, S+P- and S+P+) and for match (target repetitions) and non-match (random words) cases. First, those target items that were unfamiliar to participants according to

their performance on the vocabulary task (see below) were excluded from the analyses. For the analysis of response latencies, only reaction times for accurate responses and falling within 2 SDs of each individual participant's data mean were included into the analysis. Responses outside 1000 ms window after catch stimulus onset were treated as misses. The accuracy hit rates were then calculated as the proportion of accurate responses to the sum of accurate and erroneous responses, thus excluding the misses. The remaining match and non-match trials per participant per condition after applying these filtering procedures were 4.45±.22 and 3.95±.3, respectively. Finally, two 3-way ANOVAs with factors Match, Semantic similarity, and Phonetic similarity were conducted for the analyses of hit rates and reaction times. In addition, we checked whether the semantic relation type (direct translation or semantic similarity) had an impact on the data. For this purpose, reaction times for the semantically related vs. the direct translation items in the S+P- condition data were compared in a 2-way ANOVA including Match and relation type as factors.

Finally, the accuracy index was calculated for data obtained in the Data obtained in the Vocabulary test was used to determine the participant's proficiency in English (Vocabulary proficiency) according to the accuracy index. This data was also used to identify target items unfamiliar for participants in the crosslinguistic and hence discard those items from further analysis.

EEG recording and preprocessing

Brain activity was recorded during the crosslinguistic priming task by means of 128 Ag/AgCl active channels connected to an actiCHamp amplifier (Brain Products GmbH, Gilching, Germany). The sampling rate was 500 Hz and the recording was performed in a frequency band from DC to 1000 Hz with screen filters applied for monitoring only. During

recordings, all electrodes were referenced to FCz. EEG signals were preprocessed using the Brainstorm software (Tadel, Baillet, Mosher, Pantazis & Leahy, 2011). Raw data was downsampled to 250Hz and a bandpass filter of 0.1 – 30Hz was applied. A visual inspection of the data was carried out in order to detect and reject bad channels (mean number and range of rejected channels per participant was 1, range= 0-3). Rejection was preferred instead of an interpolation procedure, given the low number of channels showing bad signal. Then, an Independent Component Analysis (ICA) was applied to remove ocular artifacts (average number of rejected ICA components: 1.65; range = 1-4). Data were re-referenced offline to average mastoid reference and a baseline correction was carried out using the 100 ms pre-prime onset (i.e., -150 to -50 ms). EEG epochs were then extracted between -150 to 650 ms post-target onset and an artifact rejection procedure was implemented on them for the removal of epochs showing amplitude values exceeding ±100 μV (mean number and range of rejected trials per condition was: S-P+: 2.88, 2.1%, range = 0-6; S-P-: 3.41, 2.5% range = 0-8; S+P+: 3.47, 2.5%, range = 1-11; S+P-: 3.18, 2.3%, range = 0-6). Finally, remaining EEG epochs were averaged per subject and per condition and ERPs were computed (average number and range of epochs included per condition: S-P+: 70.11, range = 67-73; S-P-: 69.59, range = 65-73; S+P+: 69.53, range = 62-72; S+P-: 69.82, range = 67-73).

ERP analysis and source reconstruction

A cluster-based random permutation method implemented in Fieldtrip (Maris & Oostenveld 2007; Oostenveld, Fries, Maris & Schoffelen, 2011) was used to test for effects of L1-L2 phonological and semantic similarity at both early and late processing stages. This method deals with multiple comparisons in space and time over long ERP segments, thus allowing to determine temporally and spatially stable clusters of significant differences between conditions

while effectively avoiding type I errors. In particular, two long ERP segments were defined, from 20 to 200 ms and from 300 to 500 ms, based on the ERP literature (reviewed above) which identified early (ranging between 30 to 200 ms) and late (around 400 ms) lexico-semantic effects during word recognition in monolinguals (MacGregor et al., 2012; Segalowitz & Zheng, 2009; Pulvermüller et al., 2001; Shtyrov & MacGregor, 2016; Peeters et al., 2013). Thus, this method served to objectively identify particular time windows showing ERP effects of semantic and/or phonological crosslinguistic similarity between prime and probe stimuli. The analysis was conducted in a stepwise fashion, as detailed below.

First, since cluster-based method only allows for pair-wise comparisons, preliminary computations were conducted in order to test main effects of phonological and semantic similarity as well as their interaction. Thus, to test main effects, an average of the two experimental conditions contributing to the same level of similarity/dissimilarity in each phonology and semantic factor was calculated for each subject, and comparisons were performed using these two averages. To analyze the interaction, the difference between phonology and semantic factors was computed separately for each level of similarity (i.e., one for the similarity condition, one for the dissimilarity condition), and then comparisons between these two differences were conducted.

In more detail, comparisons between resulting averaged conditions were carried out in each ERP segment defined (20 – 200 and 300 – 500 ms) by means of non-parametric *t*-tests. These *t*-tests were computed for every sample point across each temporal segment (across 5715 sample points for the 20 – 200 ms segment, i.e., 45 time samples × 127 channels, and across 6350 sample points for the 300 – 500 ms segment, i.e., 50 time samples × 60 channels). Those samples below or equal to a predetermined alpha level (0.05) were grouped together based on

spatial and temporal adjacency (a minimum of 3 adjacent sample points was required). The cluster effect size was then calculated by taking the sum of all individual *t*-test values of every temporo-spatial grouping (or cluster). In order to correct for multiple comparisons, a cluster-based test statistic method was then implemented. In particular, the null distribution of cluster-level statistic was calculated by randomly assigning ERP segments to the experimental condition (here, 1000 times). A new cluster effect size was calculated after each randomization and the cluster with the largest effect size entered in the distribution. The proportion of cases in which the values of this distribution are larger than the observed cluster-level statistic represents the probability of the null hypothesis, which is computed for each observed cluster. If this probability is below or equal to a predetermined threshold (here, 5 %) then the null hypothesis is rejected, and the observed cluster considered significant.

Second, once a cluster of differences was detected in either of the ERP segments and its latency identified, the mean amplitude of each individual condition (S-P+, S-P-, S+P+ and S+P-) was computed over the cluster time interval and extracted. Subsequent repeated measures 4-way ANOVAs were computed on the averaged data over the corresponding time window identified by means of cluster analyses (see Results section for details), and including semantic (S+/S-) and phonological factors (P+/P-) as well as anteriority (average of 9 channels across anterior-to-posterior regions: fronto-central [FT/FC electrode line], central [T/C line], centro-posterior [TP/CP] and posterior [P] channels for the early time window, and additional frontal [F line] and posterior-occipital [P/PO line] for the late time window) and laterality (average of 9 channels across left-to-right regions including left, central and right) and as topographical factors. For those factors for which sphericity assumption resulted violated, corrected degrees of freedom by means of Greenhouse-Geisser correction and corresponding epsilon values are reported.

Finally, an estimation of the brain sources responsible for the effects found at scalp level was carried out by means of the Minimum-Norm Estimate method (MNE, Hämäläinen & Ilmoniemi, 1994) as implemented in Brainstorm. Current source density maps were obtained for each subject and condition at the specific time window showing significant differences at sensor level. These maps, representing the current density magnitudes (ampere per square millimeter), were calculated on a realistic head model (BEM) including 4025 nodes, defined in regular distances within the gray matter of the standard MRI (Montreal Neurological Institute's average brain). The obtained current density maps were then contrasted between conditions by means of paired *t*-tests.

3. Results

Behavioral results

The LEAP-Q data for self-reported proficiency are shown in Table 1. Mean proficiency was 7.6 ±1.4, with a median of 7.5 (out of 10). Vocabulary test data revealed a percentage of errors of 14.3±1.9%, with a median of 14%. Thus, both indices indicated a high level of L2 proficiency.

Analysis conducted on catch trials revealed a significant main effect of Match ($F(1,16)=9.86$, $p=.006$, partial $\eta2=.38$) and a significant 3-way interaction Match x Semantics x Phonology ($F(1,16)=5.12$, $p=.038$, partial $\eta2=.24$) for reaction time data. Subsequent pair-wise t-tests for the examination of this interaction showed that the response was faster for match than for non-match condition and that within match condition, the response was also faster for S+P- than for S+P+ or S-P- conditions ($p=.047$ and $p=.017$, FDR corrected). Analysis carried out for

accuracy data showed no significant hit rate effect (Match: $F(1,16)=1.68$, Semantics: $F(1,16)=.297$, Phonology: $F(1,16)=1.40$).

The reaction time analysis carried out for the comparison between direct translations vs. semantically related words in S+P- condition showed a significant Match effect ($F(1,7)=42.18$, $p<.001$, partial $\eta 2=.858$) whereas no effect of the Relation type was found ($F(1,7)=.034$). Thus, this data revealed no differences in the response pattern caused by direct translations and semantically related words.

ERP results

Cluster-based permutation analysis carried out in the early ERP segment revealed a significant difference between semantically similar and semantically dissimilar L1-L2 conditions ($p=.033$). This difference was detected between 40 to 60 ms, maximum at 50 ms, and most pronounced over centro-posterior scalp sites, showing lower, more negative amplitudes for semantic match L1-L2 pairs than semantically mismatching ones. No other significant differences were found for the main effect of phonological similarity or the interaction. The analysis on the late ERP segment, in turn, resulted in significant differences between both phonologically similar and dissimilar pairs ($p=.006$) as well as between semantically similar and dissimilar conditions ($p=.048$). The phonological similarity effect was detected between 380 – 444 ms and most expressed at right frontocentral scalp sites, indicating more positive-going amplitudes for phonologically similar than dissimilar L2-L1 pairs; the difference between semantically similar and dissimilar L1-L2 pairs was found between 312 to 356 ms and most pronounced over central scalp sites, revealing more negative amplitudes for semantic match than for semantic mismatch. No significant interaction between phonology and semantics was found ($p>.05$).

Subsequent 4-way rmANOVAs were carried out with the mean amplitude of each condition (S-P+, S-P-, S+P+ and S+P-) over the two time windows (40 – 60 ms and from 310 – 445) identified by means of cluster-based permutations. In particular, an early 40 – 60 ms time window was selected based on the semantic similarity effect identified by cluster analysis at that exact time-period (no other effects for phonological similarity or the interaction were identified). The late time window was selected from 310 – 445 ms, a temporal range comprising both significant effects of semantic (312 – 356 ms) and phonological similarity (380 – 444 ms) previously identified by means of cluster analysis. For the 40 – 60 ms time window, the 2 x 2 x 4 x 3 rmANOVA revealed a main effect of semantic similarity ($F(1, 16)=4.58$, $p=.048$, partial $\eta^2=.22$, $1-\beta=.52$) and significant interactions of semantic x anteriority ($F(1.36, 21.82)=4.86$, $p=.028$, $\varepsilon=.45$, partial $\eta^2=.23$, $1-\beta=.63$) and semantic x laterality ($F(2, 32)=3.53$, $p=.041$, partial $\eta^2=.18$, $1-\beta=.61$). Follow-up comparisons in this time window for the effect of semantic similarity across each anterior-to-posterior and each left-to-right region indicated this effect was higher at the centro-posterior region ($F(1, 16)=10.57$, $p=.005$, partial $\eta^2=.39$, $1-\beta=.86$). In particular, semantic similarity between L1-L2 words elicited lower, more negative amplitudes as early as 40 ms post stimulus onset than the dissimilarity condition. Neural source reconstruction carried out at this early latency revealed that this effect was likely generated at the left temporal cortex, particularly at the left middle temporal gyrus (BA21, -69, - 29, -1), left superior temporal cortex (BA41, -70, -20, 5) and left angular gyrus (BA 39, -57, -43, 24; see Figure 2).

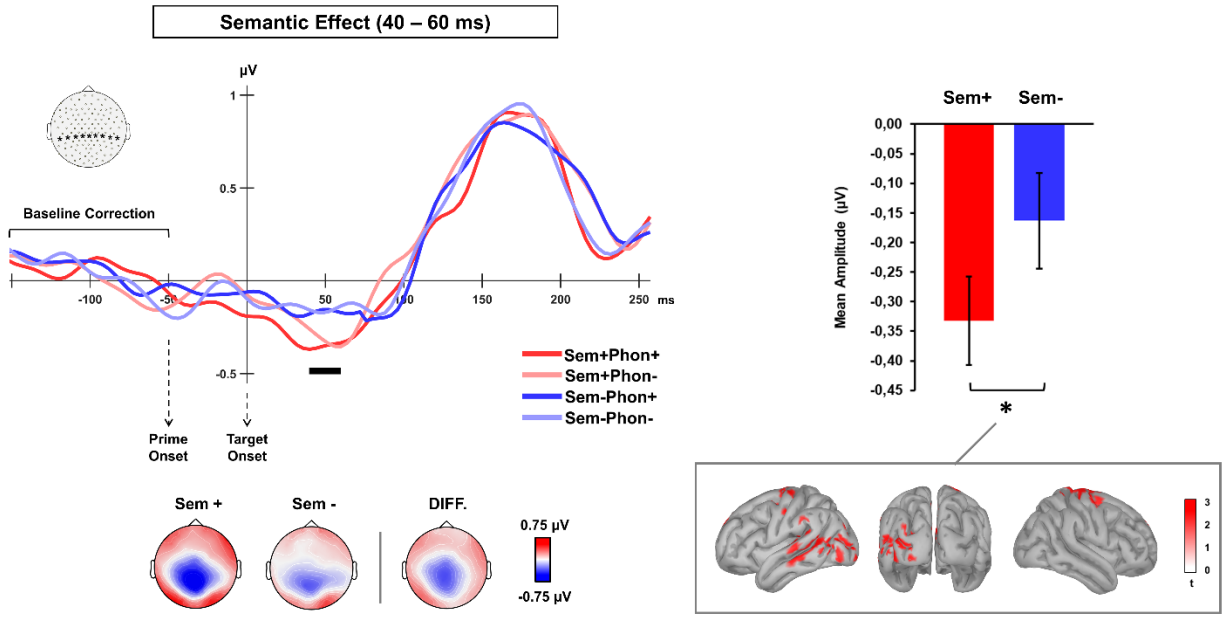

Figure 2. Averaged ERP waveforms at centro-posterior scalp sites in which the semantic similarity effect yielded significance (channels are highlighted in the template at the left upper part). The black rectangle indicates the latency of the semantic similarity effect from 40-60 ms post-target onset. Topographic maps below the ERP waveforms represent scalp distribution of each condition of semantic L1-L2 match (Sem +) and mismatch (Sem-) and their difference, collapsing both levels of phonological similarity. The bar graph shows the mean amplitude elicited by each condition at the 40 – 60 ms over significant channels. T-maps below depict the brain regions showing significant differences for the contrast between Sem+ and Sem- conditions. The 100-ms pre-prime interval (i.e., -150 to -50 ms) was used for baseline correction.

Regarding the late time window (310 – 445 ms), the 2 x 2 x 6 x 3 rmANOVA revealed significant interactions of phonology x anteriority (F(2.46, 39.39)=10.24, p=.000, ε =.49, partial η^2=.39, 1-β=.99), semantics x phonology x laterality (F(1.80, 28.94)=4.41, p=.024, ε =.90, partial η^2=.21, 1-β=.68) and semantics x phonology x anteriority x laterality (F(4.12, 65.99)=3.067, p=.021, ε =.41, partial η^2=.16, 1-β=.78). Follow-up comparisons for the semantics x phonology x anteriority x laterality interaction across each topographic region indicated higher significance of the semantics x phonology interaction at the mid-central region (F(1, 16)=10.69, p=.005, partial

η^2=.40, 1-β=.86). Pair-wise comparisons conducted in this mid-central region indicated Sem-Phon+ elicited more positive-going amplitudes than Sem-Phon- and than Sem+Phon+ (see Figure 3). Brain source estimation carried out at this late time window revealed the left inferior frontal gyrus (BA 45; -43, 36, 9) and the left lingual gyrus (BA18; -13, -106, 7) as the brain areas responsible for the phonological similarity effect, obtained from the contrast between Sem-Phon+ and Sem-Phon- conditions. Besides that, the left temporal pole (BA 38; -38, 23, -39) and the left orbitofrontal (BA 11; -21, 45, -20) were found as the brain regions showing maximal differences for the contrast between Sem-Phon+ and Sem+Phon+ conditions.

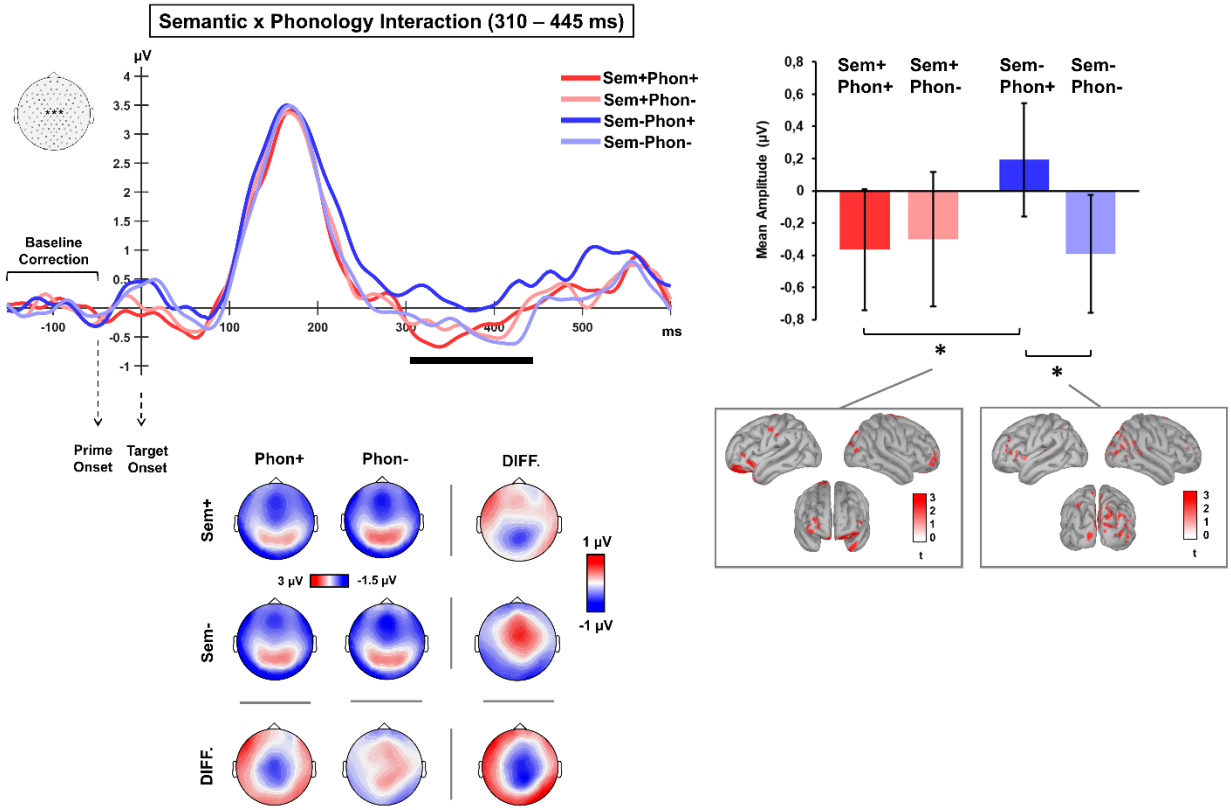

Figure 3. Averaged ERP waveforms at midline central scalp sites where the interaction between semantic and phonological similarity yielded significance (channels are highlighted in the template at the left upper part). The black rectangle indicates the latency of the semantic x

phonology interaction effect from 310-445 ms post-target onset. Topographic maps below ERP waveforms represent scalp distribution of each individual condition (S+P+, S+P-, S-P+ and S-P-) as well as the differences between conditions. The bar graph shows the mean amplitude of the N400 elicited by each condition over significant channels. T-maps below depict the brain regions reaching significant differences for contrasts between the semantic (S+P+ vs. S-P+) and phonological (S-P+ vs. S-P-) similarity conditions. The 100-ms pre-prime interval (i.e., -150 to -50 ms) was used for baseline correction.

4. Discussion

The present EEG investigation addressed the neurophysiological correlates of L1-L2 interactive word access in late bilinguals. In particular, we focused on early and late ERP effects of the phonological and semantic similarity between L1 and L2 words using a masked-priming crosslinguistic task in order to tackle the putative existence of shared neural lexicon representations for both languages. More importantly, the temporal dynamics of such interactivity during bilingual's visual word recognition was scrutinised by testing, millisecond by millisecond, effects of L1-L2 similarity throughout the ERP dynamics. Not only did our findings replicate classical effects of crosslinguistic interactions expressed as a late (~400 ms) modulation of the N400 component; they also revealed the earliest ERP effect (~50 ms) reported so far for L1-L2 interactivity at the semantic level. Furthermore, these crosslinguistic effects were also revealed at behavioral level and, importantly, shown to be underpinned by neural sources in a set of perisylvian regions typically involved in language processing. These findings support the existence of an integrated language network in the bilingual brain and, importantly, reveal the speed and automaticity of the interplay between L1 and L2. A more detailed examination of these results is provided below.

The semantic similarity between masked subliminal L1 primes and supraliminal L2 targets was found to modulate an ERP deflection as early as 50 ms post-target onset, with more

negative-going amplitudes for semantically similar than dissimilar targets. Importantly, in the absence of any difference between conditions at their low-level physical properties, the only variable accounting for such early modulation can be the semantic (dis)similarity between L1 and L2 words. Early negativities have been consistently reported to reflect automatic word memory trace activation (MacGregor et al, 2021; Shtyrov and MacGregor, 2016, Shtyrov et al, 2014), and they were shown to be stronger for words than for pseudowords (Pulvermüller et al, 2001) as well as for more familiar/frequent words than less familiar ones, reflecting the strength of connections in the memory circuits (Alexandrov et al, 2011, 2020; Shtyrov et al, 2011). This suggests that the negative-going increase in early ERP amplitude reflects a higher degree of initial activation of L2 word representations as a result of facilitation by a semantically related L1 prime. This, in turn, suggests the existence of robust links between L1 and L2 representations that can function automatically even when the L1 word is presented subliminally. Moreover, this automatic crosslinguistic interplay at semantic level may be of a general nature rather than being directly affected by the specificity of the semantic relation between prime and target, since our data indicate no differences in the pattern caused by either L1-L2 direct translations and crosslinguistic semantic neighbors in the two languages. In other words, the present ultra-fast ERP modulation may be caused by pre-activation of an overlapping conceptual network for L1 and L2 word representations, facilitating the automatic lexico-semantic access for the L2 targets semantically related to the preceding L1 primes.

Furthermore, the finding of left temporoparietal brain areas (namely, the middle temporal gyrus, superior temporal areas and left angular gyrus) as brain sources of the early modulation supports our interpretation of this early effect as a neural index of automatic lexico-semantic access as these areas have been widely reported to be involved in lexico-semantic processing and

conceptual retrieval (e.g., Patterson, Nestor & Rogers, 2007; Price & Mechelli, 2005; Binder, Desai, Graves & Conant, 2009; Davey et al., 2015). The same network has been found as a neural substrate of early (i.e., below 200ms) lexico-semantic effects in previous L1 studies (Hauk et al., 2006a, Hauk et al., 2006b). Indeed, the left angular gyrus, found here as one of the most likely brain sources of the early deflection for semantic L1-L2 similarity, has been claimed to be a critical region for the efficient automatic retrieval of semantic information (Davey et al., 2015).

Previous research on monolinguals has reported the modulation of a similarly early ERP negativity in response to semantic manipulations, and hence considered to reflect the interactive nature of the linguistic processing in L1 (Hauk et al., 2006a, Hauk et al., 2006b; Hauk et al., 2012; Penolazzi et al., 2007; Sereno et al., 2003; Segalowitz & Zheng, 2009). Such negativity has been typically found between 120 and 200 ms, and even earlier (around 100 ms) in some cases (e.g., Pulvermüller et al., 2001). Nonetheless, the 50-ms semantic effect reported in the present study is considerably earlier than most of the previous findings. One possible reason for the emergence of such an early effect is a tight match between the prime-target pairs, which were, crucially, identical across priming conditions. Since early ERP modulations are typically small in amplitude and short-lived, they can easily fall victim of stimulus variability that can smear these transient effects in time or even cancel them out completely by averaging across diverse stimuli (Pulvermüller and Shtyrov, 2006). Indeed, unlike N400 effects which often last hundreds of milliseconds, early ERP deflections may only last 10-20 ms, which is also the case here. By applying a strict control over stimulus properties, the present paradigm helped to bring out these important ultra-rapid signatures of L1-L2 interaction.

Another possible explanation for such early latency might be the masked-priming task itself, which could have promoted implicit stimulus processing to a larger degree, in which the

automaticity of the subliminal L1 processing could lead to faster onsets in the processing of related L2 words. Indeed, similarly fast (e.g., 30-70 ms) ERP modulations have been found in previous studies when using unattended exposure to linguistic stimuli, both in visual (Shtyrov & MacGregor, 2016) and spoken domains (Shtyrov & Lenzen, 2016), indicating ultra-early automatic lexico-semantic access during word recognition in the native language. Importantly, the early modulation reported here constitutes a neural correlate of such automatic lexico-semantic access in the L2, which indicates a high degree of speed and automaticity in crosslinguistic L1-L2 interactions. This contrasts with previous studies focused on semantic crosslinguistic effects, that were typically focused on the modulation of the well-established N400 component, hence reporting effects in this late rather than in other earlier ERPs; thus, the rapid interactivity in the bilingual brain has remined unnoticed so far (e.g., Antúnez, Mancini, Hernández-Cabrera, Hoversten, Barber & Carreiras, 2021; Martin, Dering, Thomas & Thierry, 2009; Hoshino & Thierry, 2012).

That said, note that one previous bilingual study did indicate a similarly early modulation in the context of a code-switching task (Jackson, Swainson, Cunnington & Jackson, 2001); in particular, a negative ERP deflection around 50 ms was reported for switch language trials in comparison to non-switch trials, although this effect was out of the scope of this study and its nature was not directly addressed in this work. The early latency of this code-switching effect is in line with that found in the present study, although both response patterns seem to be reversed. Indeed, whereas Jackson's et al. reported more negative amplitudes for switch (i.e., non-related) than non-switch trials, the early negativity observed in the present study was found for the automatic detection of the semantic L1-L2 match across prime-target pairs. Crucially, such divergent pattern might be caused by the different manipulation carried out in the two studies. In

this sense, it is possible that the different nature of the tasks conducted in both studies enhanced participant's attention towards different stimuli characteristics, thus triggering such early detection mechanism in different conditions. That is, given the task, such as Jackson's et al., in which the experimental manipulation is the linguistic switch, the divergence between languages in mismatch trials seems to trigger participant's attention, being reflected at such early negativity. However, in the present study semantic correspondence between primes and targets was systematically manipulated leading to an enhancement of the participants' attention, as reflected in the early negativity effect. Therefore, such an early effect observed in both studies is likely reflecting the enhancement of participant's attention given a particular experimental manipulation (either to encounter a different language or to encounter two divergent languages that *share* the same semantics). Nonetheless, given such differential pattern of results, more research is needed to elucidate these findings and further clarify the functional significance of such early brain activity modulation in bilinguals, both during linguistic and domain-general cognitive processing.

Besides the early modulation, a later ERP effect for a crosslinguistic phonological-semantic interaction was found in the present study. This finding is in line with previous work deploying more conventional methods of ERP analysis (Novitskiy et al., 2019) as well as a replication of previous crosslinguistic N400 priming effects using homophones (Carrasco-Ortiz et al., 2012; Jouravlev et al., 2014b; Novitskiy et al., 2019). In particular, more positive-going N400 amplitudes were obtained for phonologically similar L2 targets in the condition of semantic mismatch, an amplitude decrease typically indicative of lexico-semantic facilitation (Deacon, Hewitt, Yang & Nagata, 2000; Kiefer, 2002; Lau, Phillips & Poeppel, 2008). Unlike the early ERP effects, reflecting automatic memory trace activation as such, the N400 effect

more likely reflect integration between different stimuli (e.g., word pairs or words in a sentence), and its amplitude increases when more effort is involved for this integration (e.g., when words are unrelated of unexpected in a given context), and drops when this integration can be achieved more easily for related stimuli. Thus, the activation of L1 phonological representations caused the pre-activation of phonologically similar lexico-semantic L2 representations, hence facilitating their processing and diminishing the N400 effect. Highly in line with this hypothesis, the left inferior frontal gyrus, an area typically related to ambiguity resolution (Acheson & Hagoort, 2013; Mollo, Jefferies, Cornelissen & Gennari, 2018) as well as to phonological processes such as the assembly of phonological codes during reading (Cornelissen, Kringelbach, Ellis, Whitney, Holliday & Hansen, 2009; Wheat, Cornelissen, Frost & Hansen, 2010), was found as the most likely brain region responsible for this facilitatory effect.

Notably, while this N400 effect was found for phonological similarity, the condition of semantic similarity did not produce a similar facilitation: more negative N400 amplitudes were obtained for the semantically similar S+P+ condition than for the S-P+ condition, with this difference likely originating at the left anterior temporal pole. Such an inverse effect was also observed in a previous study (Novitskiy et al., 2019) and could be a product of the experimental manipulation used for the S+P+ condition, namely, the use of transliterations. Indeed, transliterations of English words into written Russian were used to achieve both phonological and semantic similarity between languages in this condition. Transliterations were considered more appropriate than cognates, since the use of English-Russian cognates involves matching complications. Thus, many cognates do not match phonetically, and the deviations in their pronunciation in both languages might cause an important confound in the results (e.g., the cognate of the Russian “лак” is “lacquer”, but its pronunciation is identical to “luck”). This

phonetic difference between cognates is actually not unique for English–Russian comparison, since true cognates become different with time in two independently developing languages. Moreover, differences in the frequency of cognates in the two languages could have led additional confounds. Besides that, transliterating foreign items in Cyrillic is a standard way of dealing with foreign words in Russian language, ubiquitous in media, literature and other written communications. However, it might still be possible that transliterations themselves, as stimuli not previously encountered, could prompt deeper lexico-semantic processing leading to enhanced N400 amplitudes, thus blurring the semantic similarity effect. More research is needed to further clarify this point through the use of different types of semantically related stimuli.

Taken together, both ERP effects reported herewith show rapid interactive activation of L1 and L2 semantic and phonological representations during reading. Furthermore, such crosslinguistic effect at both semantic and phonological level was also reflected in behavioral outcomes obtained in the delayed matching task. These results replicate those found in previous monolingual masked priming studies (for reviews, see Coltheart, Rastle, Perry, Langdon & Ziegler, 2001; Frost, 1998; Grainger & Jacobs, 1999; Rastle & Brysbaert, 2006), indicating representational interplay within L1 as well as between L1 and L2. Taken together, findings obtained both at behavioral and ERP level consistently indicate the integration of semantic and phonological representations in a common lexicon in the bilingual brain.

Importantly, these data support interactive models of bilingual processing, such as the BIA+ model (Dijkstra & Van Heuven, 1998, 2002; Van Heuven & Dijkstra, 2010), which postulates an integrated bilingual lexicon in which words are activated in parallel in both languages. This model posits that during visual word recognition words are activated based on their similarity with the sensory input, independently of the specific language. Therefore, the

ERP similarity effects found here are highly compatible with these predictions, with prime-target similarity between L1 and L2 words in their phonological and semantic features causing facilitation in the processing of L2 targets. Moreover, the present results reported here also highlight the interactive nature of such L1-L2 interplay, with the semantic facilitation observed at both early and late stages of stimulus processing. This, in turn, points to a two-stage semantic processing in L2, similar to that observed in monolinguals (e.g., Dambacher et al., 2006), with an early stage likely involved in the automatic access to lexical and semantic properties and a later, and likely more controlled stage related to contextual integration processes. Thus, our data support interactive activation models for visual word recognition, with semantic properties activated at early stages of visual word recognition simultaneously with other low-level (e.g., letters, word-form) features (e.g., Grainger & Holcomb, 2009; Harm & Seidenberg, 2004).

In summary, the present investigation provides new evidence for the temporal dynamics of the interactivity between L1 and L2 in the context of a single-word reading task, operationalized here using masked-priming paradigm. Our data support a common neural substrate for word representations in L1 and L2 and highlight the remarkable speed and automaticity of such crosslinguistic interactions, with semantic L1-L2 similarity detection taking place in the bilingual brain as early as ~50 ms and likely underpinned by left-hemispheric temporoparietal regions. Nonetheless, given the limited spatial resolution of EEG, future research using neuroimaging methods with higher spatio-temporal resolution (e.g., MEG with MR-based source reconstruction or fMRI-EEG combination) is required to further shed light on the neuroanatomical substrate and spatio-temporal dynamics of L1-L2 crosslinguistic interactions. Moreover, future studies may allow a more detailed characterization of the novel findings reported here by investigating whether individual differences in the bilingual experience

play a modulatory role on the intensity, timing and altogether appearance of ultrarapid crosslinguistic phenomena. Indeed, bilingualism research is moving towards an increasingly multifaceted and individualized operationalization of the bilingual experience (e.g., DeLuca, Rothman, Bialystok & Pliatsikas, 2019; Gallo et al., 2021; Sulpizio, Del Maschio, Del Mauro, Fedeli & Abutalebi, 2020). This trend, originally suggested as a solution to inconsistencies characterizing research on the consequences of bilingualism for executive control, is gaining growing popularity. The aim is to grant a better understanding of bilingualism-induced neurocognitive effects by achieving an increasingly refined operationalization of such an intrinsically multifaceted variable as bilingualism, as proven by the remarkable interindividual variability in bilingual profiles (see Gullifer & Titone, 2020; Luk & Bialtsok, 2013 for discussion). In the case of our investigation, one cannot exclude those global effects may be driven by only part of the sample, such that individual bilinguals are distinct from the aggregate pattern depending on interindividual differences in their bilingual experience. Future research is thus needed to further unveil the underlying mechanisms of this newly-found ultrarapid effects in the bilingual mind.

Declarations of interest

None.

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Appendix

A. Full set of materials used in the crosslinguistic masked-priming task.

List 1	List 2	List 3	List 4	List 5
бас	BUS	рейс	PIPE	пайп
блажь	BLUSH	стыд	CROP	кроп
блат	BLOOD	кровь	RAMP	рамп
бой	BOY	мяч	POOL	пул
боль	BALL	шар	COOK	куг
брасс	BRASS	медь	CAST	каст
бред	BREAD	хлеб	MATE	мейт
бриг	BRICK	дом	MESH	мешь
бук	BOOK	чтец	HEAD	хед
вид	WHEAT	серп	DEAL	дил
вол	WALL	вал	BOW	бау
вошь	WASH	кран	SAKE	сэйк
гад	GUT	слизь	BOOST	буст
гам	GUM	вкус	FLOOR	фло
глаз	GLASS	хруст	DEBT	дебт
год	GOD	бог	SIGN	сайн
гост	GHOST	дух	LEAP	либ
гриб	GRIP	хват	MESS	мес
гриф	GRIEF	грусть	SWEAT	свид
дичь	DITCH	ров	STEEL	стил
дол	DOLL	пупс	PLOY	плой
дот	DOT	код	SQUAD	сквод
клок	CLOCK	час	BED	бед
кол	CALL	зов	TRUST	траст
край	CRY	вой	LAND	лант
крест	CREST	склон	NOON	нун
крик	CREEK	ключ	SACK	сэк
кросс	CROSS	храм	PITCH	пич
круг	CROOK	вор	UNCLE	анкл
лаз	LASS	дщерь	CRUST	краст
лай	LIE	ложь	JOB	джоп
лак	LUCK	рок	BLOW	блоу
лист	LIST	смотр	PEACE	пиз
лов	LOAF	нож	HAND	ханд
лось	LOSS	грусть	BROOK	брук
мид	MEAT	хрящ	MOSS	мос
мозг	MOSQUE	шпиль	GUST	гаст
мол	MALL	шик	BLAST	бласт

ночь	NOTCH	щель	COP	коб
паз	PUS	гной	DAME	дэйм
пат	PART	часть	SCALE	скэйл
пик	PICK	ход	SKILL	скил
плот	PLOT	сказ	FOG	фог
пол	POLL	спрос	PORCH	поч
поп	POP	треск	TRAY	трей
пот	POT	пар	TOY	той
рай	RYE	рожь	WEEK	вик
рог	ROCK	твердь	SLOT	слод
род	ROT	гниль	PORK	порк
рост	ROAST	жар	GAZE	гэйз
сан	SUN	луч	VAN	вэн
свод	SWAT	гнус	LID	лид
скот	SCOT	килт	WOOD	вуд
слив	SLEEVE	плащ	PUMP	памп
снег	SNACK	сыр	FORK	форк
сок	SOCK	след	HALF	хаф
соль	SOUL	ад	GUN	ганн
сон	SONG	песнь	JUMP	джамп
стог	STOCK	склад	SPOT	спот
стол	STALL	конь	FAULT	фолт
стон	STONE	грот	FATE	фейт
суд	SOOT	пыль	CRAFT	крафт
тик	TICK	клещ	TWIN	твин
тип	TIP	чай	STING	стинк
ток	TALK	спор	KNOCK	ног
тол	TOLL	звон	TRUNK	транк
трак	TRUCK	ввоз	SLACK	слек
труп	TROOP	строй	GAP	гэп
трус	TRUCE	мир	HELL	хелл
хам	HUM	гул	REIGN	райн
шаг	SHACK	хлам	STAND	стант
шип	SHIP	флот	AUNT	ант
шут	SHOOT	ствол	NEED	нитт