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Second-language word recognition in noise: Interdependent neuromodulatory effects of semantic context and crosslinguistic interactions driven by word form similarity

Sara Guediche[a,*], Angela de Bruin[b], Cesar Caballero-Gaudes[a], Martijn Baart[a,c], Arthur G. Samuel[a,d,e]

[a] Basque Center on Cognition Brain, and Language, Donostia-San Sebastian 20009, Spain
[b] University of York, York YO105DD, United Kingdom
[c] Department of Cognitive Neuropsychology, Tilburg University, P.O. Box 90153, 5000 LE Tilburg, the Netherlands
[d] Stony Brook University, NY 11794-2500, United States
[e] Ikerbasque Foundation, Spain

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ABSTRACT

Spoken language comprehension is a fundamental component of our cognitive skills. We are quite proficient at deciphering words from the auditory input despite the fact that the speech we hear is often masked by noise such as background babble originating from talkers other than the one we are attending to. To perceive spoken language as intended, we rely on prior linguistic knowledge and context. Prior knowledge includes all sounds and words that are familiar to a listener and depends on linguistic experience. For bilinguals, the phonetic and lexical repertoire encompasses two languages, and the degree of overlap between word forms across languages affects the degree to which they influence one another during auditory word recognition. To support spoken word recognition, listeners often rely on semantic information (i.e., the words we hear are usually related in a meaningful way). Although the number of multilinguals across the globe is increasing, little is known about how crosslinguistic effects (i.e., word overlap) interact with semantic context and affect the flexible neural systems that support accurate word recognition. The current multi-echo functional magnetic resonance imaging (fMRI) study addresses this question by examining how prime-target word pair semantic relationships interact with the target word's form similarity (cognate status) to the translation equivalent in the dominant language (L1) during accurate word recognition of a non-dominant (L2) language. We tested 26 early-proficient Spanish-Basque (L1-L2) bilinguals. When L2 targets matching L1 translation-equivalent phonological word forms were preceded by unrelated semantic contexts that drive lexical competition, a flexible language control (fronto-parietal-subcortical) network was upregulated, whereas when they were preceded by related semantic contexts that reduce lexical competition, it was downregulated. We conclude that an interplay between semantic and crosslinguistic effects regulates flexible control mechanisms of speech processing to facilitate L2 word recognition, in noise.

1. Introduction

Spoken language comprehension is fundamental to human communication and development and is effective on a global-scale, even across different linguistic communities. The main task any listener faces is deciphering words from an auditory input. Although typical-hearing adult listeners perform this task with seemingly effortless precision, many factors can jeopardize the ability to accurately decode the speech signal and extract the intended meaning. For example, background noise, such as the "speech babble" of simultaneous speakers can significantly impair word recognition. This can have an even more detrimental effect when listening in a non-native language (Golestani et al., 2009; Lecumberri et al., 2010; 2014; Scharenborg and van Os, 2019; Tabri et al., 2015)—unless listeners are highly proficient bilinguals (Reetzke et al., 2016; Shi 2015). Consider a noisy airport or train station: A traveler achieving his/her goal of getting to a specific destination often depends on accurate recognition of noisy words delivered through a speaker system, and the message may not be broadcast in the traveler's primary language. How does a traveler optimize listening, under such challenging conditions? Fortunately, communication does not rely on isolated words but rather involves the integration of sets of words that are strung together in a semantically meaningful way. This semantic re-

* Corresponding author.
E-mail address: s.guediche@bcbl.eu (S. Guediche).

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lationship serves as a constraining context that boosts word recognition under adverse listening conditions (Clos et al., 2014; Guediche et al., 2016; Mattys et al., 2012; Obleser et al., 2007; Zekveld et al., 2011).

Language proficiency and context, however, are not the only factors that affect word recognition. Importantly, word recognition in a non-native or non-dominant (L2) language is also influenced by interactions with the dominant language (L1) (e.g., Caramazza and Brones, 1979; Costa et al., 2000; Lagrou et al., 2011; van Hell and de Groot, 2008; van Hell and Dijkstra, 2002). Most accounts of bilingual lexical processing predict increased effects of crosslinguistic lexical interactions with increasing word form overlap in sound (phonology) between L2 words and their L1 translation equivalents (Dijkstra et al., 2019; van Heuven, 2005; Shook and Marian, 2013; van Hell and Dijkstra, 2002); in keeping with the literature, we will refer to this phono-lexical-semantic overlap (i.e., overlap in form and meaning) as *phonological* 'cognate status'. Despite the increasing prevalence of second language communication, the implications of an L1-L2 functional architecture with crosslinguistic lexical-lexical interactions (Kroll et al., 2010) on the flexible systems that support accurate word recognition via lexical-meaning interactions remain unexplored. To address this issue, the current multi-echo functional magnetic resonance imaging (fMRI) study investigates the neural systems that enable early proficient bilingual listeners to benefit from semantic context and accurately recognize L2 words, in noise, as a function of the phono-lexical overlap with L1 translation equivalents (cognate status).

1.1. Effects of noise on word recognition

Across studies of spoken language processing, effects of different types of noise including white noise, pink noise, speech-shaped noise and speech-babble, have been investigated. The energetic masking properties of the latter two have made them the most commonly used manipulations in studies of auditory word recognition (see Scharenborg and van Os, 2019 for discussion). Following this practice, the current study employs six-talker speech babble, reversed in time to eliminate the potential confounding effects of the babble's meaningful content.

Noisy listening conditions create uncertainty and increase the set of possible mappings activated by the incoming speech signal, which leads to increased lexical competition, especially among similar sounding items. Consequently, the demands on cognitive resources increase (Mattys et al., 2012; Rönnberg et al., 2010), taxing a network of brain regions involved in working memory, lexical retrieval, competition, selection, conflict monitoring and error detection (Rönnberg et al., 2010; Salvi et al., 2002; Zekveld et al., 2012). This network consists of several brain regions including the inferior frontal gyri, the anterior cingulate, and the supramarginal gyrus, to name a few. In particular, the inferior frontal gyrus (IFG) has been repeatedly implicated in the comprehension of speech in noise, in both monolinguals and bilinguals, showing increased activation with decreasing signal-to-noise or intelligibility (Bidelman and Dexter 2015; Chiarello et al., 2018; Golestani et al., 2013; Rysop et al., 2019; Vaden et al., 2013).

1.2. Semantic context effects on word recognition in noise

As the speech signal unfolds, resolving ambiguity due to noise, and selecting among competitors can be constrained by available semantic context. Context facilitation effects on recognition processes are still not well understood and continue to be investigated across different perceptual domains. A current widely accepted framework grounded in neuroscientific evidence postulates that a preceding context generates predictions encoded in neural signals that have "top-down" modulatory effects, which interact with "bottom-up" predictions derived from feedforward processing of sensory input (Friston, 2010). Although the underlying neural mechanisms for semantically-mediated contextual facilitation are still debated, its effect on the comprehension of speech in noise has been associated with increased activity in regions involved in lexical and/or semantic processing. These include the middle and/or inferior temporal gyrus, the angular gyrus, and inferior and middle frontal gyri (e.g., Obleser et al., 2007; Golestani et al., 2013; Guediche et al., 2016). The benefit of semantic context for L2, in noise, does not seem to be present for non-proficient or late bilingual listeners (Golestani et al., 2009; Hervais-Adelman et al., 2014; Kousaie, 2019). However, recent work shows that semantic context *is* beneficial to L2 listeners, if they are early proficient bilinguals (Dijkgraaf et al., 2017; Kousaie et al., 2019; Guediche et al., 2020). Given that "feedforward-feedback" interactions are mediated by prior knowledge (e.g., lexical information), which for bilinguals includes any co-activated items across their two languages, there should be an interplay between factors that influence crosslinguistic interactions and semantic context effects. This interplay should, in turn, contribute to the dynamics of L2 word recognition in noise.

Consistent with this view, evidence from behavioral studies (albeit sparse) has shown an interaction between crosslinguistic and context effects on bilingual word recognition accuracy (Bultena et al., 2014; Chen and Marian, 2016; Dijkstra et al., 2015; Guediche et al., 2020; Lagrou et al., 2013). For example, following an unrelated semantic context, cognates were detrimental to noisy L2 auditory word recognition (Guediche et al., 2020). This result may seem counterintuitive given the number of visual word recognition studies (and fewer auditory word recognition studies) that have shown facilitation effects of cognate status (see review by Dijkstra, 2005), but all of those studies used clear stimulus presentation conditions. Presumably, in the case of noisy listening, the unrelated context generated a number of competitors, and crosslinguistic form overlap led to an even larger pool of lexical competitors that extended to include items from both languages (Guediche et al., 2020). If this is the case, the critical question is how interactive effects of semantic context and crosslinguistic activation are reflected in the recruitment of language and control brain networks during accurate word recognition, in noisy conditions.

1.3. The present study

To begin to unravel this question, the current study uses fast event-related, multi-echo multi-band functional magnetic resonance imaging (fMRI) to investigate the potential interplay between semantic priming effects and crosslinguistic phono-lexical overlap during *accurate* L2 word recognition, in noise. Using a standard fMRI semantic priming paradigm, a group of highly proficient Spanish-Basque L1-L2 early proficient bilinguals performed a lexical decision task on targets in noise (reversed speech babble). Each target was preceded by a clear semantically-related or unrelated prime, and presented through MR-compatible headphones.

Targets were counterbalanced across both semantic conditions, across participants, enabling comparisons between Related and Unrelated conditions that only differ in the semantic relationship or the degree of L1 phono-lexical overlap. This procedure equates for other possible target stimulus-related confounds. Our design also attempted to minimize irrelevant stimulus-related effects by controlling for additional lexical characteristics (e.g., phonological neighborhood density) across different conditions. We also ensured that the onset of the noisy target always occurred at the same timepoint of the TR to prevent potential conflating effects of differences in "noise masking" across trials, which could result from irregularities in the level of scanner noise associated with image acquisition (of multiple echoes), across the duration of any given TR. Finally, fMRI methodological studies have shown that the ability to detect activity in regions previously implicated in speech intelligibility depends on the scanning protocol (Evans and McGettigan, 2017; Halai et al., 2015); a multi-echo scanning sequence that uses an optimal combination of the multiple echoes has been shown to be advantageous. For this reason, we used a multi-echo (4 echoes), multiband (3), continuous scanning sequence for the functional data acquisition. This method enhances the ability to detect changes in BOLD signal, in regions more susceptible to signal loss such as those involved in semantic processing and cognitive control (e.g., inferior temporal gyrus, orbital frontal cor-

tex). We expect this procedure to reveal a more complete picture of the regions involved in L2 word recognition, regions that are sensitive to the interactive effects of interest between semantic context and L2-L1 word form overlap.

2. Methods

2.1. Participants

32 highly proficient Spanish-Basque bilinguals participated in the experiment. The experiment was approved by the BCBL Ethics Review Board and complied with the guidelines of the Declaration of Helsinki. All participants provided written consent and were paid for their participation.

Two participants moved excessively within a run during the fMRI scanning session, three participants performed at or below chance on target words, and one participant only completed half of the experiment. The data from the remaining 26 participants (18 female, Mean age = 26.23, SD = 4.93) were included in the analyses. All participants reported typical hearing and right-hand dominance. All participants acquired Spanish from birth and reported Spanish dominance. Self-reported Basque acquisition was between 0 and 7 years old (M = 2.1, SD = 1.7). Language proficiency in Basque and Spanish was assessed with a 65-item picture-naming test (Basque mean score= 58.73 out of 65, SD = 4.27; Spanish mean score = 64.8 out of 65, SD = 0.61) and an interview (Basque mean score = 4.54 out of 5, SD = 0.51; Spanish mean score = 5, SD = 0). Both proficiency measures form part of the BEST (de Bruin et al., 2017) and are collected when participants first sign up to take part in any experiments at the BCBL. We also report individual subjective measures of exposure (self-rated time spent) to Basque compared to Spanish, as well as separate measures provided for hearing, speaking and reading (see Appendix for individual language profiles). Taken together, the measures of age of acquisition, proficiency and exposure indicate that all participants are Spanish-dominant.

2.2. Experimental design

Procedure. Participants listened to auditory stimuli through MR-compatible headphones. Each trial included a Basque word (the prime) presented in the clear followed by a Basque word or pseudoword (the target) (ISI = 300 ms) presented in reversed speech babble. Word Targets were mixed with unique bits of six-talker Basque Speech Babble, which was reversed (sound file played backwards) using Goldwave (Goldwave Version 6.15 Computer software, www.goldwave.com). The signal-to-noise ratio was 0 dB, based on pilot testing to identify a level that would avoid both floor and ceiling effects. Each target was mixed with a unique segment of the babble, and included a preceding 50 ms of ramp-up and a following 50 ms of ramp-down of the babble (for more details about the mixing procedure, see Guediche et al., 2020).

The stimulus set consisted of 320 Prime-Target pairs. The words used in this study were taken from a larger set used in a previous behavioral study (Guediche et al., 2020). Participants performed a two-alternative forced-choice (2-AFC) lexical decision task (LDT) and were instructed to respond as quickly and as accurately as possible by pressing one button if the target was a word, and another button if the target was a pseudoword; they were not to respond to the first item in the pair. Participants were given six practice trials prior to the start of the experiment. The practice items were not included in the main experiment.

All of the word targets were Basque words. The targets differed in the degree to which they overlapped in phonological form with their translation equivalent. Words with overlapping form are referred to as cognates and can either be partially overlapping (Partial-cognates) or fully overlapping (Identical-cognates). The remaining words were non-overlapping in form (Non-cognates). Of the word targets, half were Non-cognates (120) and half were Cognates (120). The cognates consisted of half identical cognates (60) and half partial cognates (60); previous work suggests that these may have different influences on lexical access (Dijkstra and van Heuven, 2002; Duyck et al., 2007). Identical cognates were words that shared 100% phonological-form overlap with their L1 translation equivalents (e.g., "koaderno" which is the word for "notebook" in Basque and is "cuaderno" in Spanish and pronounced the same), whereas Partial cognates were words that shared > 50% and < 100% overlap (e.g., "lore" is the word for "flower" in Basque, versus "flor" in Spanish). Conveniently, L1 and L2 (Spanish and Basque) have a high degree of overlap in their sound structure, largely sidestepping conflating effects of lower-level crosslinguistic phonetic differences, which are more pronounced in other language combinations.

There were no significant differences between words of different Cognate types for measures of Basque phonological neighborhood density Identical-cognates [M = 5.0, SD (5.6)], Partial-cognates, [M = 5, SD (4.8)], Non-cognates [M = 6.4, SD(5.7)]; Imageability Identical-cognates [M = 2.9, SD (3.2)], Partial-cognates [M = 3.8, SD (2.9)]; Non-cognates [M = 4.2, SD (2.8)], age of acquisition [Identical-cognates (M = 3.3, SD (0.4)], Partial-cognates [M = 3.1, SD (0.5)]; Non-cognates [M = 2.9, SD (0.5)]; and Basque log word frequency measures which were available for > 89% of the words, Identical-cognates, [M = 1.0, SD (0.5)], Partial-cognates [M = 1.3, SD (0.7)], Non-cognates [M = 0.9, SD (0.6)], $p > .05$.

Half of the word targets were preceded by a Related prime word (e.g., "baratze-tomate", which is Basque for "vegetable garden-tomato") and half were preceded by an Unrelated prime word (e.g., "arkatz-tomate", which is Basque for "pencil-tomato"). The semantically related primes were designed with the help of a native Basque research assistant. The semantic relationship between the primes and targets was measured using Latent Semantic Association (LSA) measures from English translations of the Basque words. LSA measures were obtained from lsa.colorado.edu using the default topic space; there were no significant differences across the different cognate conditions, $p > .6$ (Identical-cognates M = 0.36, SD (0.17), Partial-cognates M = 0.37, SD (0.20); Non-cognates M = 0.36, SD (0.19)). To create the Unrelated condition, the primes were randomized. Thus, across participants, targets were counterbalanced across Related and Unrelated conditions in two different randomized lists so that all words (Primes and Targets), were heard in different conditions. Each participant heard 60 Related and 60 Unrelated Non-cognates, 30 Related and 30 Unrelated Partial-Cognates, and 30 Related and 30 Unrelated Identical-Cognates. All of the primes were Noncognates. An additional 120 Prime-Target pairs consisted of Filler Non-cognate Basque word primes and Pseudoword targets (derived from a separate set of Non-cognate Basque words) which were included for the purposes of the lexical decision task. All items were delivered through MR-compatible in-ear headphone set at approximately 90 dB(A).

Paradigm. A fast event-related design with three jitter conditions for trial lengths of 6, 12, and 18 s and interspersed TRs of rest was optimized based on a multi-objective randomization approach using genetic algorithms; the algorithm optimizes the design according to the detection, efficiency, stimulus frequency and predictability (Kao et al., 2009; Kao and Zhou, 2017). Stimulus presentation was controlled with PsychoPy version 1.38 (Peirce, 2007). Each run consisted of 80 trials, of which 20 were Related (10 Noncognates, 5 Partial Cognates, 5 Identical Cognates), 20 were Unrelated, and 40 were Filler trials. Participants were assigned to one of the two lists, from the Related/Unrelated counterbalancing described above. The first experimental trial followed an 18 s delay. There was a 300 msec interval between each prime and target. Each prime ended at the TR pulse so that the onset of the targets occurred 300 ms after a TR pulse to minimize the potential that scanner-noise would mask the already noisy target stimulus. Participants were given 4 s to respond from the start of the target stimulus (see Fig. 1). The average durations of the word targets and their preceding primes were M = 1.039 s, (SD = 0.111 s) and M = 0.955 s, (SD= 0.147), respectively.

MRI acquisition: MRI data was acquired in a 3 Tesla SIEMENS MAGNETOM Prisma-fit scanner equipped with a 64-channel head coil.

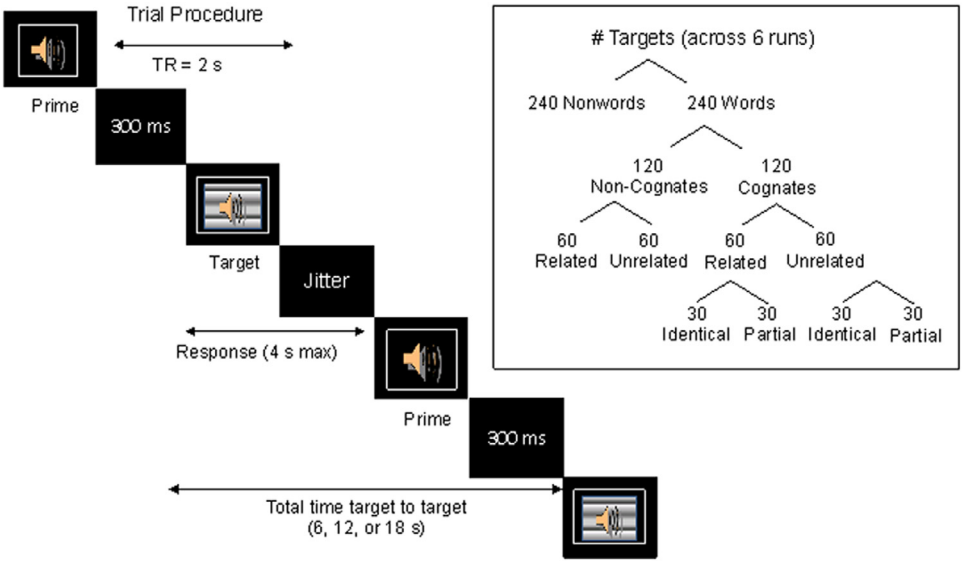

Fig. 1. Example of trial procedure and target stimulus conditions.

A T1-weighted MPRAGE structural image (voxel size = 1 × 1 × 1 mm^3, 176 slices, field of view = 256×256 mm^2, TE = 2.36 ms, TR = 2530 ms, flip angle = 7°; GRAPPA = 2, acceleration factor 7/8) was acquired for anatomical alignment during preprocessing. T_2*-weighted functional images were acquired using a simultaneous multi-slice multi-echo (ME) gradient-recalled echo-planar imaging (EPI) sequence developed by the Center for Magnetic Resonance Research (CMRR, Minnesota, USA) (Moeller et al., 2013; Setsompop et al., 2012) (TEs = 11.8, 29.89, 47.98, 66.07 ms, TR = 2000 ms, flip angle = 70º, multi-band factor = 3, voxel size= 2.4 mm isotropic resolution, FOV = 210×210 mm^2, GRAPPA = 2 with 24 reference lines and gradient-echo reference scan mode, Partial Fourier = 6/8, Bandwith = 2368 Hz/px, 63 contiguous axial slices with interleaved acquisition, MB LeakBlock kernel optimization (Cauley et al., 2014) and SENSE R = 1 algorithm for SNR-optimized coil combination (Sotiropoulos et al., 2013) allowing for full brain coverage). Twenty participants completed all six full functional runs, and six participants completed only 5 valid runs, each 10 min and 24 s long (i.e., 312 vol). In addition, a single-band reference image was acquired in each run to use for motion realignment and normalization to the anatomical image. For each run, two spin-echo EPI scans (TR = 2000 ms, TE = 30 ms, flip angle = 70º, refocus flip angle = 180º) with opposing phase-encoding directions (anterior-posterior (AP) and posterior-anterior (PA)) and the same voxel coordinates and volume acquisition were acquired for geometric distortion correction. Physiological traces of respiration and cardiac pulse were also collected during the acquisitions, for the purposes of future methodological investigations.

2.3. MRI data preprocessing

AFNI (Cox, 1996) (version 18.02.16) was used for data preprocessing in the following order using an adapted version of the afni_proc.py script: 1) slice-timing correction, 2) computation of spatial transformations: (a) geometric distortion correction using the AP and PA scans on a by-run basis; (b) realignment of 1st echo functional scans to 1st echo distortion-corrected single-band reference image of the first run (reference image); (c) co-registration of reference image to the skull-stripped T1-w image; (d) affine and non-linear warping of T1-w image to MNI 152 2009 template; and (e) if necessary, an additional de-obliquing transformation was also computed to obtain good functional-anatomical co-registration; 3) the spatial transformations were combined and applied once to co-register the functional images to the MNI space, 4) T2*-based optimal combination of the echoes (Posse et al., 1999), and 5) spatial smoothing of within-brain voxels with a 5-mm Full-Width-Half-Maximum Gaussian kernel. In these steps, the functional mask was obtained based on the 1st echo single-band reference image which allowed for better delineation of brain voxels, especially in the anterior and inferior temporal lobe and cerebellum.

Definition of regions of interest. The ROIs were chosen based on their involvement in speech perception, semantic context effects, and lexical and language control processes. Six regions of interest (ROIs) (see Fig. 2) were defined on each participant's MNI-transformed anatomical image. The transverse temporal gyrus, involved in the processing of the "bottom-up" auditory input (Warrier et al., 2009; Zatorre et al., 2002), was defined using the Talairach and Tournoux (1998) (TT_Daemon) atlas built into AFNI. The other five regions were defined using the CA_ML_MNI atlas built into AFNI which subdivides different sections of Left Inferior Frontal Gyrus (LIFG), left pars orbitalis triangularis, and opercularis, each of which have different hypothesized contributions to language (including phonological, lexical and semantic processing). Badre et al. (2005) associate pars triangularis with selection mechanisms related to lexical competition, and pars orbitalis to "top-down" controlled retrieval processes. Two ROIs in parietal lobule areas were also included: the left angular gyrus that is thought to contribute to semantic processing (Seghier et al., 2010) and is sensitive to semantic context effects in monolingual listeners and bilinguals listening to L1 (Clos et al., 2014; Golestani et al., 2013; Hervais-Adelman et al., 2014; Kousaie et al., 2019; Obleser et al., 2007), and the left supramarginal gyrus, which is thought to be involved in working memory and control processes. All ROIs were resampled to the voxel resolution of the functional images and used to extract the condition-specific beta coefficients.

Definition of seed regions for condition-dependent functional connectivity analysis (gPPI). From our regions of interest, the two frontal areas most implicated in cognitive aspects of language processing, pars triangularis and pars orbitalis, were used as seed regions in a generalized psychophysiological interactions (gPPI) analysis (McLaren et al., 2012) (see also https://afni.nimh.nih.gov/CD-CorrAna). These have been shown to be part of different networks in bilingual language control during word production (Branzi et al., 2020). A third seed region was the left transverse temporal gyrus, involved in perceptual processing of speech stimuli (Warrier et al., 2009; Zatorre et al., 2002).

2.4. Statistical analyses

Subject-level data analysis. Univariate analyses were based on individual general linear models for each participant and included regressors of interest using the target onset times for each condition's

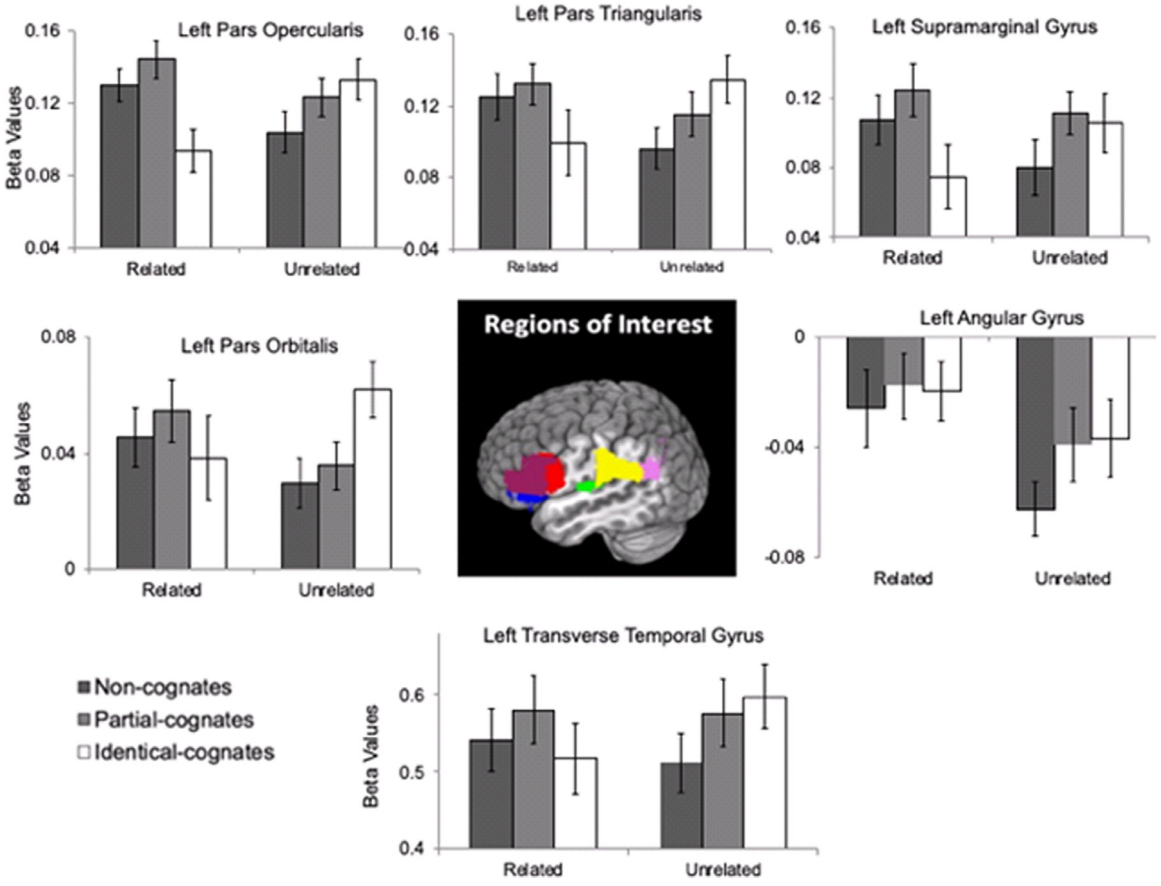

Fig. 2. Anatomically defined regions of interest. The frontal areas include the pars orbitalis (blue), pars triangularis (purple), and pars opercularis (red). Parietal areas include supramarginal gyrus (yellow) and the angular gyrus (pink). The temporal area is transverse temporal gyrus (green).

(Filler, Related Identical, Related Partial, Related Non-cognate, Unrelated Identical, Unrelated Partial, Unrelated Non-cognate) correct and incorrect responses (these included no-response trials), separately. These target onset times were convolved with a duration-modulated gamma function that accounted for trial-specific prime and target auditory stimulus durations. Regressors of no-interest included the six realignment parameters and their derivatives, as well as Legendre polynomials up to 5th order. Any time points that exceeded a threshold of 0.3 in the Euclidean norm of the temporal derivative of the realignment parameters were omitted from the GLM analysis, as well as the first nine time points of each run, which did not consist of any stimulus presentation, to allow the signal to achieve steady state magnetization.

Univariate Group-level data analysis. Beta coefficients for each condition for correct responses were entered into a 2 × 3 Semantic Context (Related vs. Unrelated prime) x Cognate Status (Non-cognates, Partial-cognate, Identical-cognate) ANOVA for both an anatomically-defined region of interest analysis as well as a voxel-wise whole brain analysis. The two types of cognates – Identical-cognates and Partial-cognates – were treated as separate factors given that (a) they have been recently shown to have different effects on the language control brain network during visual word recognition (see Peeters et al., 2019), and (b) behavioral evidence shows differences in their effect on lexical access (Dijkstra and van Heuven, 2002; Duyck et al., 2007).

For the whole-brain analysis, individual subjects' noise smoothness was estimated from the residual time series and averaged. A mixed autocorrelation function was used (Cox et al., 2017) in Monte Carlo simulations using a Group mask (removing ventricles and brainstem) applied to the ANOVA results. At a voxel-wise threshold of $p = .001$, clusters of > 33 voxels were considered to be significant at a cluster threshold with an alpha value of 0.05. Any other reported clusters that do not survive this threshold are marked accordingly in Table 2.

gPPI Subject-level data analysis. The timeseries from each seed ROI (left pars triangularis, left pars orbitalis and left transverse temporal gyrus) was extracted, detrended with Legendre polynomials of up to 5th order, and the neuronal-related timeseries (physiological regressor) was estimated via deconvolution using the Gamma function as a model of the hemodynamic response. Next, physio-psychological interaction regressors were created by multiplying the condition files (with 1′s and 0′s where 1′s code the presence of a given condition) for each of the 7 conditions' correct trials (Filler, Related Identical, Related Partial, Related Non-cognate, Unrelated Identical, Unrelated Partial, Unrelated Non-cognate) with the deconvolved timeseries of the seed region.

For each subject, a GLM analysis was performed including the seed timeseries as well as the interaction regressors, in addition to the previous regressors of interest and no-interest defined for the subject-level data analysis. These included target onset times convolved with a duration-modulated gamma function, with separate regressors for correct and incorrect responses for each condition. Again, the regressors of no-interest included 6 motion parameters and their derivatives, for each run, as well as Legendre polynomials up to 5th order. Similarly, censored time points were omitted from the GLM analysis.

gPPI Group-level data analysis. To better understand the functional connectivity patterns that mediate the *crossover* interaction patterns observed in the region of interest and whole brain analyses (see below), we assessed the condition-specific functional connectivity patterns at the group level. The interaction effects from the univariate group analysis showed that the crossover pattern was driven by one of the cognate conditions (Identical-Cognates). Thus, the beta values associated with each interaction regressor for the conditions that showed the crossover

pattern were entered into a 2 × 2 Semantic Context (Related, Unrelated) x Cognate Status (Non-cognate, Identical-cognate) ANOVA analysis.

To identify target regions whose functional connections were sensitive to an interaction between semantic priming and cognate, from the pre-defined seed regions, a more lenient voxel-wise threshold of $p = .05$ was required. However, as in the whole brain analysis, individual subjects' noise smoothness was estimated from the residual time series of the gPPI regression for each seed region, and averaged applying the mixed autocorrelation function (Cox et al., 2017) in Monte Carlo simulations using a Group mask (removing ventricles and brainstem) applied to the ANOVA results. This approach addresses the issues raised by Eklund et al. (2016) related to an inflation of Type I errors in fMRI results. The cluster threshold was defined at an alpha value of 0.05, resulting in significant clusters > 782 voxels for the left orbitalis, > 806 for left triangularis, and > 785 for left transverse temporal gyrus.

3. Results

To better understand the neural circuits that support accurate L2 word recognition in noise, the results of the three fMRI analyses that probe the neural interactions between Semantic context and Cognate Status are presented below. The first set of fMRI results presented is from the anatomically-defined regions of interest analysis, the second of a whole-brain voxelwise analysis, and the last characterizes the condition-dependent functional connectivity of two frontal regions, left pars orbitalis and left pars triangularis, and the left transverse temporal gyrus (gPPI analysis). Before turning to the fMRI results, which pertain only to accurate responses, the results of the behavioral data collected during scanning are briefly presented.

3.1. Task behavioral results

The aim of the fMRI analysis was to understand the recruitment of different brain regions as a function of semantic context and cognate status, for accurately recognized words. Yet, it is important to characterize the effect of these factors on behavioral responses as well. Raw word accuracy data were submitted to a repeated-measures 2 (Semantic context; related vs unrelated prime) x 3 (Cognate Status; Noncognate, Partial-Cognate, Identical-Cognate) ANOVA. Overall response accuracy for word targets was (68.7%, SEM = 2.3) and for pseudoword targets was (83.0%, SEM= 1.9). The main effect of Semantic context was significant $F(1,25) = 67.29$, $p < .001$: accuracy was higher for targets following related (74.1%, SEM= 2.3) vs. unrelated primes (64.5%, SEM= 2.4). The main effect of Cognate Status $F(2,50) = 4.07$, $p = .02$ was also significant: accuracy was highest for Non-cognates (71.0%, SEM = 2.4), followed by Partial-cognates (68.7%, SEM = 2.3), and Identical-cognates (66.6%, SEM = 2.7). The interaction between Semantic context and Cognate Status was not significant. However, the numerical pattern of the results was consistent with a previous behavioral study (Guediche et al., 2020) showing *reduced* accuracy for cognates in noise following an *unrelated* context, and no difference between cognates and noncognates following a related context. There were several differences between this study and the behavioral studies worth mentioning that could contribute to a less robust effect: Due to the noisy scanner environment, a lower SNR was used here (0 dB compared to −5 dB), and the participants' L2 age of acquisition was slightly more variable Guediche et al. (2020). To gain insight into the early proficient Spanish-Basque (L1-L2) lexical and semantic bilingual functional architecture, we turn to effects on brain responses produced during accurate word recognition. Specifically, we tested for the interaction between crosslinguistic and semantic effects.

3.2. fMRI results

L2 word recognition is affected by both crosslinguistic interactions and semantic context effects (e.g., Dijkstra and van Heuven, 2002; Dijkstra et al., 2019; Kroll et al., 2010; Shook and Marian, 2013). If the neuro-functional architecture is interactive in nature, like that proposed for monolingual word recognition processes (Hickok and Poeppel, 2007), these two effects could interact with one another in noisy conditions which increase reliance on context. Thus, our aim was to investigate the potential interactive effect on changes in brain activity between these two factors. As mentioned in the introduction, listening to speech in noise increases reliance on predictions generated from semantic context and prior lexical knowledge, decreasing cognitive effort and facilitating accurate word recognition. Thus, we predicted that frontal and parietal areas implicated in predictive and cognitive control processes, and auditory areas involved in early perceptual processing of the noisy speech input, would be sensitive to interactions between these two factors.

Table 1 shows the results from the 2 (Semantic Context: related vs. unrelated prime) × 3 (Cognate Status: Non-cognate, Partial-cognate, Identical-cognate) ANOVAs on the activation of six regions of interest that included three left frontal regions of interest, two left parietal regions, and the left transverse temporal gyrus. All three frontal regions of interest, the supramarginal gyrus and the transverse temporal gyrus showed a significant interaction between Semantic Context and Cognate Status. All frontal ROIs showed a similar pattern to one another; identical-cognates produced greater activation compared to non-cognates, in the unrelated context. In contrast, for related prime-target pairs, a decrease in activation for identical cognates compared to non-cognates was found, resulting in a crossover interaction pattern (see Fig. 2). Pars opercularis, the frontal region most implicated in phonological processing (Heim et al., 2009) also showed a main effect of Cognate Status. The crossover pattern was only found for Identical-cognates and not for Partial-cognates, consistent with previous reports showing differences in their effect on the activation of frontal areas and other regions associated with language control during word recognition (Peeters et al., 2019).

Turning to parietal regions of interest, the angular gyrus, a semantic processing area that has been shown to be sensitive to semantic context effects on speech in noise in bilinguals' L1 (Hervais-Adelman et al., 2014) showed only a significant main effect of Semantic Context, with greater activation for Related than Unrelated Context. However, the supramarginal gyrus, which has been considered to be part of a fronto-parietal control network (Yeo et al., 2011) showed a significant interaction similar to that found in frontal areas.

The left transverse temporal gyrus, associated with speech perceptual processing (Warrier et al., 2009; Zatorre et al., 2002), showed a main effect of cognate status, driven largely by differences in the Unrelated context, as well as a significant interaction effect (see Fig. 2). The activation pattern increased in a graded fashion as a function of L2-L1 cognate status when preceded by an unrelated semantic context, suggesting sensitivity to the degree of crosslinguistic phono-lexical interactions. However, when preceded by a related context, there were no significant differences in activation pattern among the different target types, consistent with the growing evidence that predictive contexts modulate perceptual processing.

Whole Brain analysis. A whole brain voxel-wise 2 × 3 Semantic Relatedness (Relatedness, Unrelatedness)

X Cognate Status (Non-cognate, Partial-cognate, Identical-cognate) ANOVA was conducted.

A main effect of Cognate Status was found in premotor, motor, and insular cortices. Bilateral premotor and insular areas showed modulation as a function of cognate status. The activation of motor structures during listening is prompted by noisy speech (Du et al., 2014), presumably reflecting increased engagement of covert articulatory processes due to increased difficulty (Wilson et al., 2009). Cognate effects on premotor and insular activation could then reflect differences in word recognition difficulty, across different word types, or differences in the degree of articulatory overlap. Of particular interest were the results of the direct contrast between cognates and non-cognates. Cognates showed greater activity than non-cognates in the superior tem-

Table 1
Results showing significant effects from 2 × 3 ANOVA for each of the anatomically-defined regions of interest.

Voxels	Regions of Interest	Interaction Effect	Relatedness Effect	Cognate Effect
956	Left Orbitalis	$F(2,50) = 4.55$, $p = .015$		
1157	Left Triangularis	$F(2,50) = 8.79$, $p = .001$		
571	Left Opercularis	$F(2,50) = 9.17$, $p < .001$		$F(2,50) = 3.4$, $p = .041$
696	Left Angular Gyrus		$F(1,25) = 6.56$, $p = .017$	
726	Left Supramarginal Gyrus	$F(2,50) = 7.47$, $p = .001$		$F(2,50) = 4.53$, $p = .016$
147	Left Transverse Temporal Gyrus	$F(2,50) = 8.94$, $p < .001$		$F(2,50) = 6.70$, $p = .003$

Table 2
Whole brain 2 × 3 Semantic Context (Related, Unrelated) x Cognate Status (Non-cognate, Partial-cognate, Identical-cognate) voxel-wise analysis showing main and interaction Effects.

Brain Regions		Cluster size	Coordinates		
			x	y	z
Main effect of Cognate Status	**F-value**				
Left Precentral Gyrus/BA 6	22.42	663	−56.4	−3.6	26.4
Right Precentral/Postcentral Gyrus/BA 6	23.13	396	+54.0	−8.4	+21.6
Left Medial Frontal Gyrus	15.85	236	−8.4	−20.4	+50.4
Right Insula	20.84	141	+37.2	−10.8	+14.4
Left Postcentral Gyrus	14.16	54	−15.6	−39.6	74.4
Cognates > Non-cognates	**T-value**				
Left STG	5.95	185	−51.6	−13.2	+4.8
Right posterior STG	5.03	86	+56.4	−22.8	2.4
Right anterior STG	5.385	77	61.2	+1.2	−4.8
Left posterior Cingulate (BA23/31)	5.23	50	−1.2	−56.4	+21.6
Noncognates > all Cognates	not sig.				
Semantic Relatedness					
Unrelated > Related					
Left medial and SFG					
mid-cingulate (BA32) †	4.62	29	−10.8	+20.4	+48.0
Related > Unrelated					
Left AG †	3.61	650	−54.0	−66.0	+38.4
Left MTG and ITG † (BA20/21)	4.80	342	−56.4	−42.0	−9.6
Semantic Context X Cognate Status	**F-value**				
Left Insula, IFG/BA45 and STG	25.03	542	−27.6	+32.4	+4.8
Right IFG/MFG/BA47	21.13	410	+37.2	+25.2	+0.0
Right posterior STG and transverse temporal gyrus	18.19	401	+58.8	−13.2	+2.4
Right IFG/BA9	19.08	218	+46.8	+8.4	+19.2
Left SFG/MFG/Cingulate	15.77	163	−10.8	+18.0	+40.8
Left Cerebellum (CrusI)	15.74	119	−15.6	−82.8	−24.0
Left MFG/BA6	14.3	84	−42.0	−1.2	+50.4
Right Cerebellum (CrusI)	15.33	62	+22.8	−82.8	−21.6
LSMG BA40/LSTG	16.39	62	−51.6	−46.8	+19.2
Left Cingulate/BA32	17.05	61	−13.2	+27.6	+28.8
Right Cerebellum (Crus II)	16.34	49	+13.2	−90.0	−31.2
Right Cerebellum(LobuleVIIa)	15.99	48	+27.6	−66.0	−40.8
Left Caudate	14.8	35	−10.8	+13.2	+7.2

Note. MNI coordinates (x, y, z) are reported for peak voxel at maximum t-value. Cluster size is in voxels. Voxel-wise threshold of $p < .001$ at a cluster size correction alpha value of 0.05 unless otherwise indicated. † Denotes regions that did not survive a cluster threshold correction of alpha = 0.05, voxelwise threshold $p < .05$. IFG= Inferior Frontal Gyrus, STG= Superior Temporal Gyrus, ITG= Inferior temporal gyrus, MTG = Middle Temporal Gyrus, AG= Angular Gyrus, SMG= Supramarginal Gyrus, MFG = Middle Frontal Gyrus, SFG= Superior Frontal Gyrus, BA = Brodmann Area.

poral gyrus and posterior cingulate cortices, bilaterally (see Table 2). In monolinguals, increased activity in STG has been associated with increased lexical competition (e.g., Rissman et al., 2003; Zhuang et al., 2014).

A main effect of Relatedness was found in a region in medial frontal cortex encompassing cingulate cortex (BA 32) showing greater activity for Unrelated compared to Related (see Table 2). Regions showing greater activity for Related compared to Unrelated conditions included the angular gyrus and the inferior temporal gyrus, which emerged at a reduced threshold ($p < .05$, uncorrected; see Table 2). Increased activation for Unrelated compared to Related pairs has been interpreted as increased conflictmonitoring in cingulate cortex (e.g., Rissman et al., 2003). In contrast, increased activity for Related compared to Unrelated pairs is associated with semantic processing or semantic context effects that reflect facilitation of lexical access/processing.

The whole-brain analysis showed a significant interaction effect in a number of regions (see Fig. 3, Table 2) including the supramarginal gyrus, bilateral frontal cortical, medial frontal gyrus, cingulate, bilateral superior temporal gyri, caudate, thalamus, and cerebellar areas. These results complement the regions of interest analysis showing that interaction effects are not only present in frontal and parietal areas associated with cognitive control but are bilateral and extend into subcortical and cerebellar regions showing a similar interaction pattern. In the field of bilingualism, this whole set of regions converges with a network of areas that has been referred to as the bilingual "language control" network (see Abutalebi and Green, 2008, 2016; and Calabria et al., 2018).

The cerebellum is often reported in studies examining context effects on spoken language processing, however only a few studies discuss its functional significance to predictive semantic contexts (though see D'Mello et al., 2017; Moberget et al., 2014). The significant interac-

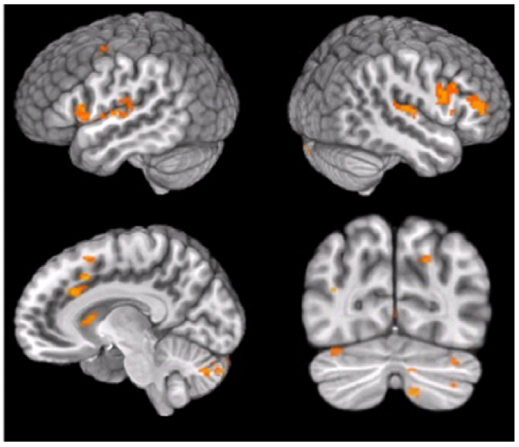

Fig. 3. Regions showing a significant interaction effect between Semantic Context and Cognate Status, at a voxel-wise threshold of $p = .001$ and corrected alpha value of .05.

tion effects found in multiple cerebellar regions may be due to the improved signal-to-noise ratio that is gained with the multi-echo sequence in the current study compared to the single echo used in other studies, as the cerebellum is susceptible to BOLD signal loss. Importantly, different subregions of the cerebellum are presumed to contribute different functions based on their connections with different cortical networks (Buckner et al., 2011; Skipper and Lametti, 2020). Of relevance, the right lateral Crus I lobule, a subregion implicated in linguistic processes and predictive processes (Moberget et al., 2014; Stoodley and Schmahmann, 2009; 2012), also shows a significant interaction effect. Interestingly, the activation pattern in the cerebellum was similar to that found in frontal regions, providing further evidence for its involvement in the language control network. Again, the crossover pattern was only found for identical-cognates, suggesting that a downregulation of the language control network occurs when acoustic predictions generated from meaning and native language phonology intersect. Thus, the connectivity analyses and discussion focus on these conditions.

A Generalized Form of Context-Dependent Psychophysiological Interactions (gPPI). Three regions were selected as seeds for a condition-dependent functional connectivity (gPPI) analysis. Two frontal regions, the left pars orbitalis and left pars triangularis were selected for their involvement in different cognitive functions involved in language processing, and the left transverse temporal gyrus was selected for its involvement in perceptual processing (Warrier et al., 2009; Zatorre et al., 2002). As mentioned in the introduction, pars orbitalis and pars triangularis are thought to have distinct functional contributions to lexical processing (Badre et al., 2005). Moreover, they have also been reported to have different connectivity profiles during bilingual word production (Branzi et al., 2020).

The results show that pars triangularis connections to RIFG and cingulate, and pars orbitalis connections to anterior and posterior cingulate (ACC, PCC), were modulated by Semantic Context, showing greater functional connectivity for targets preceded by Unrelated compared to Related primes (see Table 3, Fig. 4). Frontal-ACC connections have also been shown to be modulated by semantic context, in monolingual language studies (Roelke and Hofman, 2020; Weber et al., 2016). In addition, an interaction effect from both frontal areas to a cluster in cingulate cortex (including posterior cingulate) was also found. Specifically, connectivity increased for identical-cognates when preceded by an unrelated compared to a related prime, suggesting a greater need for cognitive control and conflict monitoring. An opposite pattern was found for non-cognates. Given the involvement of cingulate structures in cognitive control, ACC in conflict monitoring (Abutalebi and Green, 2008), and PCC in inhibition (Talati and Hirsch, 2005) and internally-directed cognition and adaptive behavior (Leech and Sharp, 2014; Pearson et al., 2011), the results suggest that both semantic context and crosslinguistic interactions regulate the involvement of language control during word recognition.

Turning to the left transverse temporal gyrus, its connections to anterior cingulate (ACC) and right Crus I were modulated by an interactive effect of Semantic Context and Cognate Status (see Table 3, Fig. 4). The left transverse temporal gyrus was positively correlated with ACC and right Crus I when targets that were identical in phonological form and meaning with L1 were preceded by a *related* semantic prime; they were negatively correlated with right cerebellar cortex and ACC when preceded by an *unrelated* semantic prime. An opposite pattern was found for non-cognate targets. The findings are consistent with the involvement of the cerebellum in predictive processing; correlations with perceptual areas are positive in contexts that point to the same predicted auditory input (i.e., both related semantic context and crosslinguistic information are congruent with one another).

4. Discussion

When speech is degraded by noise, listeners rely on context and prior knowledge to generate intersecting predictions that optimally map the incoming acoustics, bolstering word recognition and minimizing cognitive effort. For bilinguals, prior knowledge includes the repertoire of words in two languages, which also influence one another during word recognition. Consequently, any L2-L1 crosstalk may affect the predictive processes that facilitate word recognition, thereby modulating the recruitment of brain regions that support flexibility in speech processing. L2 word recognition tends to be more affected by noise than L1, but early, proficient bilinguals seem to be more resilient to noise and also benefit from semantic context effects on word recognition accuracy (Kousaie et al., 2019; Guediche et al., 2020) unlike non-proficient L2 listeners (Hervais-Adelman et al., 2014). The current fMRI study of early proficient Spanish-Basque (L1-L2) bilinguals sought to shed light on bilingual functional architecture and identify the neural systems involved in *accurate* L2 word recognition, in noise. Specifically, we investigated the potential for neural interactions resulting from the interplay between semantic context and L2-L1 connections as a function of a word's cognate status (which reflects the degree of phonological overlap for translation equivalents) for accurately recognized noisy L2 words. The results provide evidence for neuromodulation of both speech and language control areas that depend on interactions between the two factors.

4.1. Semantic and crosslinguistic effects on brain activation

We first examined six regions of interest, which included three left inferior frontal (IFG) areas: pars opercularis, triangularis, and orbitalis, which have been implicated in different aspects of language processing, bilingual language control (e.g., Abutalebi and Green, 2008, 2016), cognitive control (Badre et al., 2005; Badre and D'Esposito, 2007; Wagner et al., 2004), as well as predictive coding (e.g., Sohoglu et al., 2012). We also examined two functionally-distinct left parietal areas involved in verbal working memory and control (supramarginal gyrus) (Yeo et al., 2011), and semantic processing (angular gyrus) (Seghier et al., 2010). In addition, we were interested in effects on lower-level bottom-up processing of the auditory speech input, in the left transverse temporal gyrus (Warrier et al., 2009; Zatorre et al., 2002).

All frontal areas showed a significant interaction effect (see Fig. 2, Table 1): Activation was enhanced for accurately recognized identical-cognates (compared to non-cognates) when they were preceded by unrelated contexts and reduced when preceded by related contexts. Thus, L2 co-activation of L1 seems to impact the predictive and control processes associated with frontal regions during accurate word recognition, in noise. The supramarginal gyrus (SMG) also showed a

Table 3
gPPI results showing significant effects from 2 × 2 Semantic Context (Related, Unrelated) x Cognate Status (Identical-cognate, Non-cognate) ANOVA on neural interaction beta coefficients.

Seed Region	Target Regions	Cluster Size	Coordinates		
			x	**y**	**z**
Unrelated > Related					
left pars orbitalis	Anterior cingulate	1111	+1.2	+32.4	−33.6
	Posterior cingulate	826	−1.2	−61.2	+36.0
left pars triangularis	Cingulate (BA 32)	1211	+1.2	+22.8	+40.8
	Right inferior frontal gyrus	857	+39.6	+20.4	+28.8
Related > Unrelated *not sig.*					
left transverse temporal gyrus	Left ant/mid MTG †	332	−61.2	−22.8	−2.4
NonCognates > ID Cognates					
left pars orbitalis	*no significant clusters*				
left pars triangularis	Cuneus/BA 18	2541	+3.6	−75.6	+4.8
left transverse temporal gyrus	*no significant clusters*				
Interaction					
left pars orbitalis	Cingulate (anterior, middle)	2759	−1.2	−34.8	+50.4
	Left cuneus/posterior cingulate	2259	−1.2	−73.2	+4.8
left pars triangularis	Left lingual gyrus/BA 18 and posterior Cingulate	1369	−3.6	−63.6	−2.4
	Cingulate (BA 32) and medial frontal	1157	+1.2	+10.8	+45.6
left transverse temporal gyrus	Right cerebellum (Crus I)	851	+27.6	−70.8	−33.6
	Anterior cingulate	842	+8.4	+51.6	+12.0

Note. Cluster size is voxels. Regions showing interaction between Semantic Context (Related, Unrelated) and Cognate Status (Identical-cognate, Non-cognate) in whole brain voxelwise ANOVA, voxelwise threshold of $p = .05$ at a cluster size correction alpha value of 0.05. MNI voxel coordinates (x, y, z) are reported at ICenter. † Denotes regions that did not survive a cluster threshold correction of alpha = 0.05.

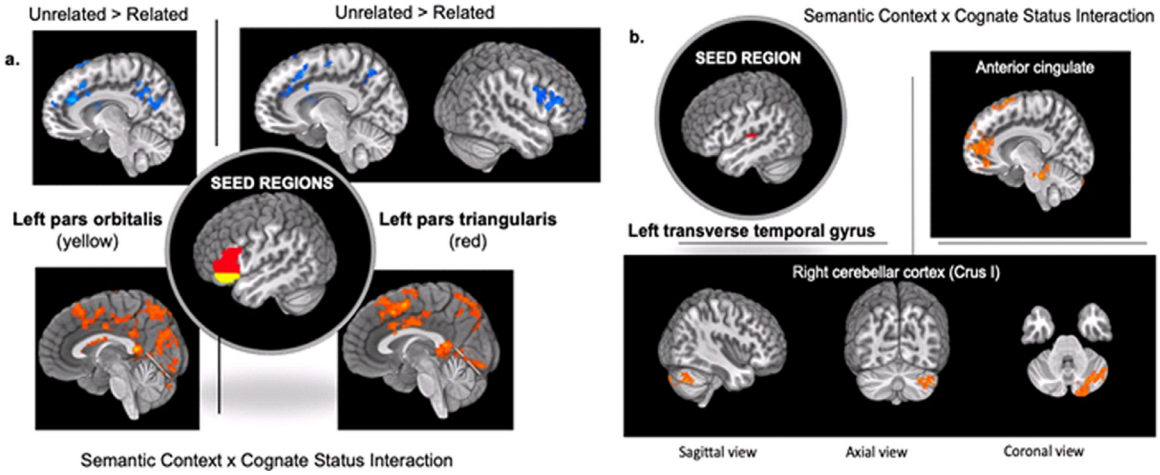

Fig. 4. Results of the gPPI analysis showing target regions three seed regions of interest **a**. Frontal seed regions = pars orbitalis (left panel) and pars triangularis (right panel). Top panel shows target regions that show Unrelated > Related connections. Bottom panel shows Semantic Context x Cognate Status (Non-cognate, Identical-Cognate) interaction effect on connections to target regions (see Table 3). The interaction reflects positive correlations for Identical-cognates in Unrelated context and negative in Unrelated context. The opposite pattern was found for Non-cognates. **b**. Temporal seed region = left transverse temporal gyrus (right panel). Interactive effect reflects positive correlations to right Crus I and ACC for L2-L1 identical-cognates in Related context and negative correlations in Unrelated context. The opposite pattern was found for non-cognates.

similar interaction effect. We note that accurately recognized partial-cognates did not show the crossover interaction; in the related context, activation was not reduced, as was the case for identical-cognates. Thus, the downregulation seems to occur when semantic-L1 interactions converge onto the same predicted phonological and acoustic input.

Notably, the angular gyrus (AG) showed a significant main effect of semantic context, demonstrating that early proficient L2 listeners rely on the same neural systems that support top-down effects in monolinguals (e.g., Kousaie et al., 2019; Matsumoto et al., 2005; Obleser et al., 2007; Rissman et al., 2003). The AG did not show a significant interaction effect like that found for the SMG, supporting the notion that they perform different functions and belong to functionally distinct networks (Yeo et al., 2011).

In the left transverse temporal gyrus, greater activation was found when comparing cognates to non-cognates. The significant interaction between semantic context and cognate status revealed that this difference was driven by the unrelated context; for a non-predictive context, activation increased with increasing word form overlap (cognate status: non-cognates < partial-cognates < identical-cognates, see Fig. 2), whereas for a predictive (related) context, there was no difference. Relevant to the current study, STG activation has been associated with lexical competition effects (Gow, 2012; Minicucci et al., 2013; Prabhakaran et al., 2006; Righi et al., 2010). Thus, one likely possibility is that, in the unrelated context, crosslinguistic interactions increase lexical competition effects by expanding the pool of activated unrelated competing candidates to include items across both languages (Guediche et al., 2020).

The whole-brain analysis was consistent with the ROI results; enhanced activity for cognates was not restricted to the left transverse temporal gyrus ROI but extended along the STG, bilaterally. Turning to the effect of relatedness, greater activation for unrelated compared to related pairs was found in the Anterior Cingulate (ACC), consistent with semantic priming effects reported in monolingual studies (e.g., Rissman et al., 2003). Based on previously reported semantic facilitation effects found for L1 speech (related > unrelated), in addition to the angular gyrus, the involvement of the left middle, inferior temporal gyrus, as well as the inferior frontal gyrus, was also predicted *a priori*. The left mid-inferior temporal gyrus, known as the "lexical interface" (Hickok and Poeppel, 2007) and implicated in semantic control (Noonan et al., 2013; Krieger-Redwood et al., 2016), showed a significant increase in activation for semantically-related compared to unrelated prime-target pairs. However, based on the rising concern for false positive compared to false negative findings in fMRI analyses (Eklund et al., 2016), we applied a very conservative cluster size correction to the whole brain analysis that addresses these concerns (Cox et al., 2017); with this correction, the cluster did not survive the stringent cluster size threshold. That this expected region, which is highly susceptible to BOLD signal loss, did show significant voxelwise $p < .05$ effects and was relatively large (> 340 voxels, uncorrected) compared to clusters reported across other semantic priming studies is likely thanks to the use of an optimal combination of multiple echoes. We believe that this result is meaningful and consistent with growing evidence that regions within the ventral (sound-to-meaning) language stream (not only regions in the dorsal stream associated with articulatory processes) contribute to context effects on speech in noise (Davis et al., 2011; Guediche et al., 2013, 2016; Hickok, 2012). The predicted semantic context effect in the inferior frontal gyrus did not emerge, showing an interaction between semantic context and cognate status instead.

In the whole brain analysis, a broad network of regions was sensitive to the interaction between semantic context and cognate status. This set of regions (excluding the superior temporal gyri) overlaps with a set of regions previously identified in bilingual studies. Within the field of bilingualism research, it has been dubbed the bilingual "language control " network (Abutalebi and Green, 2008, 2016; Calabria et al., 2018). Although the neuro-anatomical framework of the language control network has been primarily based on language production tasks, recent work (including the current study) has also revealed increased involvement of control regions (including IFG and ACC) in bilingual comprehension tasks (Bidelman and Dexter, 2015; Blanco-Elorrietta and Pylkkänen, 2016; Kousaie et al., 2019). Specifically, when task conditions promote activation of the non-target language during bilingual word recognition (e.g., language switching), there seems to be a greater need for control areas (Garcia et al., 2018; Peeters et al., 2019) activated along with the superior temporal gyrus.

While the region of interest analysis was restricted to regions in the left hemisphere, the whole-brain results clearly show involvement of the right hemisphere. The involvement of the right hemisphere (including right frontal regions) is in line with more recent models of bilingual language control (Green and Abutalebi, 2016) including the right prefrontal cortex (whereas Abutalebi and Green's 2008 model focused on the left prefrontal cortex). This suggests that bilingual language control might rely on a bilateral network. However, this might not just apply to bilinguals. Word recognition studies in monolinguals also show bilateral activation in response to lexical competition (e.g., Righi et al., 2010; Luthra et al., 2019).

The current study's use of a multi-echo scanning protocol, with whole-brain coverage, seems to be sufficiently sensitive to identify condition differences in regions normally susceptible to signal loss including the frontal orbital cortex and the cerebellum, belonging to established control networks (e.g., Buckner et al., 2011). Multi-echo scanning procedures may help to rectify the concerning trend for null findings in language research. Decades of language research focused only on perisylvian cortex (see review by Price et al., 2012) and have overlooked other parts of the cerebrum, the cerebellum and other subcortical structures. Indeed, many previously reported language-related effects may involve larger networks than what has been previously thought. Some early neuroimaging studies of language also focused only on the left-hemisphere.

4.2. Frontal functional connections

Previous studies have shown that frontal and temporal connections are modulated as a function of context effects on low quality speech (Obleser et al., 2007; Sohoglu et al., 2012). Thus, the next set of analyses aimed to characterize the nature of any potential frontal and temporal functional connectivity changes associated with our experimental manipulations. In a recent study (Branzi et al., 2020), functional connectivity analyses showed that left pars triangularis (a.k.a, mid-vlPFC) and left pars orbitalis (a.k.a, anterior-vlPFC) were differentially modulated by semantic context during L2 word *production*. An unrelated semantic context increased left pars orbitalis connections to ACC and PCC, and left pars triangularis connections to right inferior frontal gyrus (RIFG) and cingulate. Branzi et al. (2020) also showed that these two frontal regions are part of distinct functional subnetworks that contribute to different aspects of lexical processing. Whereas ACC is involved in conflict monitoring (Abutalebi and Green, 2016), the RIFG is associated with inhibitory control (Xue et al., 2008) and language inhibition (de Bruin et al., 2014). Here, semantic context, during word *recognition*, seems to modulate two frontal pathways that together likely serve to 1) monitor conflict and detect errors, and 2) inhibit interference among lexical competitors (including those co-activated in L1). Finally, both regions showed interactive effects on functional connections with cingulate/midline areas. The results suggest that when there is a need for increased conflict resolution and cognitive control, (e.g., for identical-cognates in the *unrelated* context), connectivity between frontal and cingulate structures increases.

4.3. Auditory functional connections

Auditory functional connections to ACC and cerebellar cortex, specifically right Crus I, were modulated by the interaction effect, as well; they increased for identical-cognates in the *related* context and decreased for the *unrelated* context. Crus I has been linked to language processing (Argyropoulos, 2016; Desmond and Fiez, 1998; Guediche et al., 2014; Stoodley and Schmahmann, 2009; Skipper and Lametti, 2020), and more specifically, in predictive semantic and lexical effects on speech processing (D'Mello et al., 2017; Guediche et al., 2015; Moberget et al., 2014). If both semantic crosslinguistic and phonological-lexical context can be used to derive internally-generated predictions, their modulation of auditory-cerebellar and ACC connections may facilitate detection of conflict and perceptual prediction errors. This circuit may, in turn, regulate the recruitment of frontal areas that help to resolve lexical competition. In fact, in other domains, conflict detection involving ACC has been shown to engage control processes (Botvinick et al., 2001; Haupt et al., 2009).

5. Summary

Taken together, the results suggest that crosslinguistic overlap and semantic context interact to influence perceptual processing and language control. Effects of crosslinguistic overlap show that L1 can influence L2 lexical processing, even though the task environment for this study was in L2. This is in line with previous research supporting language non-selective access during comprehension in single-language contexts (e.g., Spivey and Marian, 1999; Thierry and Wu, 2007).

The observed interaction effects show that crosslinguistic effects on L2 processing might depend on the surrounding semantic context; full crosslinguistic overlap in an *unrelated* semantic context might increase lexical competition and involvement of language control (fronto-

parietal-subcortical network) while a *related* context might have the opposite effect. This interaction may reflect the congruence of internally-generated predictions derived from available contextual and bottom-up information, and thus may not be unique to bilinguals. Interestingly, frontal areas are also sensitive to interactions between semantic and phonological stimulus manipulations that affect lexical competition, in monolingual studies (Minicucci et al., 2013; Rogers and Davis, 2017). Furthermore, as found here, interactive modulatory effects on both frontal-ACC and left temporal-cerebellar connections have been reported in monolinguals (Luthra et al., 2019). While L2 phonological properties of the stimuli were not explicitly manipulated here, they vary according to their relationship with the dominant language.

6. Conclusion

The neural systems involved in accurate L2 auditory word recognition are indeed sensitive to interactions between semantic context and L1 word knowledge. The findings paint a picture whereby the language control network and perceptual processes work in concert to facilitate word recognition through converging predictions derived from semantic context and the co-activation of L1. Semantic-crosslinguistic interactions also modulated auditory functional connections to ACC and cerebellar cortex, which likely facilitate conflict and error detection, and consequently recruit other language control areas. Accordingly, language control is upregulated when an unrelated semantic context drives lexical competition and cognate word forms promote crosslinguistic interactions. In contrast, it can be downregulated when predictions generated by semantic context and L1 converge onto the same mapping of the acoustic signal.

Overall, the findings suggest that accurate word recognition in contexts that promote increased lexical competition (e.g., unrelated context combined with noise) can result in a greater 'cognitive cost' for L2 when stimulus properties promote crosslinguistic lexical interactions with L1; a meaningful context can eradicate this 'cost', at least for early proficient listeners. Returning to the case of a noisy travel announcement, a congruent context will generate expectations that guide optimal listening performance for a proficient L2 listener, but if the context is incongruent, the listener will have to 'work harder' to recognize a word that overlaps in its phono-lexical form with the L1. These findings translate to other practical implications. For example, bilingual educational settings could be designed to improve comprehension not only by optimizing the listening conditions, but also by enriching the semantic cues of the learning environment. These conclusions, however, should take into consideration the fact that Spanish and Basque share a high degree of overlap in their acoustic and phonological properties, as well as in their orthography. Crosslinguistic interaction may depend on language similarity, thus, future work is required to determine whether the same neural patterns are observed across different bilingual groups.

Declaration of Competing Interest

The authors declare no competing financial interests.

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Data Availability

Data will be made available upon request. There are no specific restrictions other than all materials shared will need to be de-identified and in compliance with the host institution policies.

Appendix

Table 1

AoA Basque	BEST Spanish	BEST Basque	Interview Basque	%L1 Exposure	%L2 Exposure	%Hear L1	%Hear L2	%Speak L1	%Speak L2	%Read L1	%Read L2
0	65	60	5	60	30	60	20	70	20	80	10
0	65	60	5	40	30	40	40	50	40	30	40
0	65	61	4	60	30	70	20	70	30	70	20
0	65	61	5	70	30	70	30	70	30	90	10
0	65	62	5	50	40	60	30	60	40	70	20
0	65	61	4	50	40	80	20	80	20	80	20
0	62	62	5	60	20	40	40	50	20	30	40
2	65	57	4	80	10	60	10	60	10	90	0
2	65	60	4	70	30	80	20	70	30	80	20
2	65	65	5	60	30	60	30	60	30	50	20
2	65	58	5	40	30	40	30	50	30	50	10
2	65	57	4	60	10	50	10	70	10	50	0
2	65	50	5	60	30	50	40	60	30	70	20
2	65	61	4	60	20	50	30	60	30	70	20
2	65	59	4	70	10	70	10	80	10	80	10
2	65	59	5	50	50	40	60	50	50	40	60
3	65	50	4	50	30	40	50	40	40	30	60
3	65	60	4	70	20	50	20	60	10	30	10
3	65	46	4	70	20	70	20	70	20	70	20
3	65	59	4	70	10	60	10	80	10	80	10
3	65	59	5	70	20	50	30	60	30	60	30
3	65	56	4	80	20	80	20	80	20	70	30
3	65	58	5	60	20	70	20	60	10	70	20
4	65	63	5	60	30	60	30	70	30	80	20
5	64	60	5	50	30	50	20	50	40	50	10
7	65	63	5	60	10	60	0	60	10	50	0

Note. The individual language profile for each participant is included in this table. AoA= age of acquisition for Basque. All participants acquired Spanish at birth. L1 is Spanish and L2 is Basque. The maximum

BEST score is 65. The fourth column labeled Interview Basque is the interview score in Basque, for which the maximum score is 5. All participants had an interview score of 5 in Spanish. The other columns refer to self-rated exposure to L1/L2 in general (0–100%) and to self-rated time spent hearing, speaking, or reading in L1/L2 (0–100%).

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