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"Neural dynamics supporting longitudinal plasticity of action naming across languages: MEG evidence from bilingual brain tumor patients"

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Corresponding Author:	Lucia Amoruso Basque Center on Cognition Brain and Language San Sebastian, SPAIN
First Author:	Shuang Geng
Order of Authors:	Shuang Geng
	Quiñones Ileana
	Santiago Gil Robles
	Iñigo Pomposo
	Garazi Bermudez
	Polina Timofeeva
	Nicola Molinaro
	Manuel Carreiras
	Lucia Amoruso

Abstract:	Previous evidence suggests that distinct ventral and dorsal streams respectively underpin the semantic processing of object and action knowledge. Recently, we found that brain tumor patients with dorsal gliomas in frontoparietal hubs show a selective longitudinal compensation (post- vs. pre-surgery) during the retrieval of lexico-semantic information about actions (but not objects), indexed by power increases in beta rhythms (13-28 Hz). Here, we move one-step further and ask whether a similar organizational principle also stands across the different languages a bilingual speaks. To test this hypothesis, we combined a picture-naming task with MEG recordings and evaluated highly proficient Spanish-Basque bilinguals undergoing surgery for tumor resection in left frontoparietal regions. We assessed patients before and three months after surgery. At the behavioral level, we observed a similar performance across sessions irrespectively of the language at use, suggesting overall successful function preservation. At the oscillatory level, we found longitudinal selective power increases in beta for action naming in Spanish and Basque. Nevertheless, tumor resection triggered a differential reorganization of the L1 and the L2, with the latter one additionally recruiting the right hemisphere. Overall, our results provide evidence for (i) the specific involvement of frontoparietal regions in the semantic retrieval/representation of action knowledge across languages; (ii) a key role of beta oscillations as a signature of language compensation and (iii) the existence of divergent plasticity trajectories in L1 and L2 after surgery. By doing so, they provide new insights into the spectro-temporal dynamics supporting postoperative recovery in the bilingual brain.

Title: "Neural dynamics supporting longitudinal plasticity of action naming across languages: MEG evidence from bilingual brain tumor patients"

Authors: Shuang Geng [1,2], Ileana, Quiñones [1], Santiago Gil Robles [3, 4], Iñigo Pomposo [4], Garazi Bermudez [4], Polina Timofeeva [1,2], Nicola Molinaro [1,2,5], Manuel Carreiras [1,2,5] & Lucia Amoruso [1,5,6 *]

[1] Basque Center on Cognition, Brain and Language (BCBL); San Sebastian, Spain

[2] Universidad del País Vasco (UPV/EHU); San Sebastian, Spain

[3] Hospital Quiron, Madrid, Spain;

[4] BioCruces Research Institute, Bilbao, Spain,

[5] Ikerbasque, Basque Foundation for Science; Bilbao, Spain

[6] Cognitive Neuroscience Center (CNC), Universidad de San Andrés, Buenos Aires, Argentina

* Corresponding author:

Lucia Amoruso

l.amoruso@bcbl.eu

Basque Center on Cognition, Brain, and Language

Paseo Mikeletegi 69, 2nd floor

20009 Donostia/San Sebastian - Spain

Highlights

- Object and action knowledge are handle via distinct ventral and dorsal systems
- Bilingual patients with dorsal tumors show selective compensation for action naming
- Longitudinal compensation is indexed by power increases in beta rhythms (13-28 Hz)
- Tumor resection triggers a differential postoperative reorganization of L1 and L2
- L2 additionally recruits the right contra-lesional hemisphere after surgery

Abstract

Previous evidence suggests that distinct ventral and dorsal streams respectively underpin the semantic processing of object and action knowledge. Recently, we found that brain tumor patients with dorsal gliomas in frontoparietal hubs show a selective longitudinal compensation (post- vs. pre-surgery) during the retrieval of lexico-semantic information about actions (but not objects), indexed by power increases in beta rhythms (13-28 Hz). Here, we move one-step further and ask whether a similar organizational principle also stands across the different languages a bilingual speaks. To test this hypothesis, we combined a picture-naming task with MEG recordings and evaluated highly proficient Spanish-Basque bilinguals undergoing surgery for tumor resection in left frontoparietal regions. We assessed patients before and three months after surgery. At the behavioral level, we observed a similar performance across sessions irrespectively of the language at use, suggesting overall successful function preservation. At the oscillatory level, we found longitudinal selective power increases in beta for action naming in Spanish and Basque. Nevertheless, tumor resection triggered a differential reorganization of the L1 and the L2, with the latter one additionally recruiting the right hemisphere. Overall, our results provide evidence for (i) the specific involvement of frontoparietal regions in the semantic retrieval/representation of action knowledge across languages; (ii) a key role of beta oscillations as a signature of language compensation and (iii) the existence of divergent plasticity trajectories in L1 and L2 after surgery. By doing so, they provide new insights into the spectro-temporal dynamics supporting postoperative recovery in the bilingual brain.

Key words: Brain tumors, Bilingualism, Action semantics, Speech production, Oscillations, MEG

1. Introduction

Semantic processing is central to everyday life as it allows humans to fluently manipulate stored knowledge and build meaning on the fly, thus supporting essential communicative functions such as language production and comprehension.

Mounting evidence from behavioral, neurophysiological and imaging studies in healthy individuals and brain tumor patients (Amoruso et al., 2021; Gleichgerrcht et al., 2016; Shapiro, Moo, & Caramazza, 2006; Vigliocco, Vinson, Druks, Barber, & Cappa, 2011) suggests that the semantic representation/retrieval of object and action knowledge is underpinned via partially distinct ventral and dorsal systems respectively involving inferotemporal and frontoparietal nodes. Interestingly, studies using electrical stimulation for intraoperative language mapping during awake brain surgery support this category-based segregation, showing greater number of errors for objects when stimulating temporal regions; and greater number of errors for actions when disrupting activity in prefrontal and parietal cortices (Corina et al., 2005; Corina et al., 2010; Lubrano, Filleron, Demonet, & Roux, 2014; Ojemann, Ojemann, & Lettich, 2002).

In a recent study (Amoruso et al., 2021), we recorded magnetoencephalographic (MEG) activity in healthy controls and patients with low-grade gliomas (LGGs) compromising either ventral or dorsal brain regions while performing a picture-naming task including object and action stimuli. Patients were evaluated in a longitudinal fashion, namely before and after surgery for tumor resection. Results from controls showed segregated beta (13–28 Hz) power decreases in left ventral and dorsal streams for object and action naming, respectively; in a time-window classically associated to lexico-semantic retrieval (~250–500ms). When longitudinally comparing patients' oscillatory MEG responses we found post-surgery beta (13–28 Hz) modulations mimicking the category-based segregation showed by healthy controls, with ventral and dorsal damage leading to selective compensation for object and action naming.

Overall, our previous findings provided evidence for the existence of two separable object vs. action semantics subsystems, and pointed to a key involvement of beta oscillations as a signature of adaptive compensation in brain tumor patients.

Yet, information about language reorganization and oscillatory compensation in bilingual speakers harboring brain tumors is scarce. Specifically, the question of whether and to what extent semantic knowledge is integrated across languages in the bilingual brain is a topic of debate. For instance, it has been suggested that the degree of overlapping across semantic representations varies depending on variables such as age of acquisition (AoA) and language proficiency. In other words, the earlier and more accurately a second language (L2) develops, the more likely it will recruit the same neural devices responsible for the first language (L1) (Abutalebi, 2008; Abutalebi & Green, 2007; Paradis, 2000; Perani & Abutalebi, 2005). Indeed, it has been shown that as proficiency improves, L2 conceptual representations become semantically processed in the same way as in the L1 (Hut & Leminen, 2017). Furthermore, imaging (Consonni et al., 2013; Hernandez, Dapretto, Mazziotta, & Bookheimer, 2001; Willms et al., 2011) and neurophysiological (Geng et al., 2022) evidence indicates that object-action distinctions are sustained by common neuroanatomical and oscillatory components across the two languages a proficient bilingual speaks, further supporting the existence of shared semantic sub-systems across L1 and L2, at least when both are mastered in a native-like fashion.

Given this evidence, in the present study we wanted to move one-step further and test the hypothesis that the semantic representation/retrieval of action-based knowledge is mainly supported via the dorsal stream and overlaps across the two languages a highly proficient bilingual speaks. To this end, we focused on brain tumor patients with dorsal lesions in fronto-parietal hubs as an experimental model. More specifically, we combined an object/action picture-naming task (Gisbert-Munoz et al., 2021) with MEG recordings and longitudinally evaluated (i.e., before and three months after surgery) four highly proficient Spanish-Basque bilinguals undergoing surgery for tumor resection.

Overall, given the involvement of the dorsal pathway in action processing, we expected to find a selective post-surgery compensation in beta rhythms (13-28 Hz) for the retrieval of action (but not object) knowledge (Amoruso et al., 2021). More critically to the present study, we expected to extend this evidence to bilingual patients and to find similar patterns of adaptive compensation across L1 and L2, indicating language-invariant semantic processing in the bilingual brain.

2. Materials and Methods

2.1. Participants

Four highly proficient Spanish-Basque bilingual patients with low-grade gliomas (LGGs) in left fronto-parietal regions took part in this study (see Figure 1 for lesion profile). Patient's demographics, clinical information and lesion characteristics are summarized in Table 1. All patients were recruited at the Cruces University Hospital (Bilbao, Spain) where they received their diagnosis and performed the awake brain surgery for tumor resection. The initial neurological exploration at the hospital revealed no severe motor, somatosensory, or linguistic deficits thus qualifying for the awake brain surgery procedure. Admission diagnoses were weakness/sensory loss in the contralesional leg in patients 1, 2 and 4; and seizure in the case of patient 3.

Patients were evaluated in two sessions: a first session one week before the surgery, and a second session approximately three/four months after the surgery. In each session, behavioral, MEG and structural MRI data were collected.

In addition, healthy-control data from sixteen highly proficient Spanish-Basque bilinguals (4 men, Mean age = 25.87; SD = 5.25) performing the same picture-naming task were reutilized from a previous study (Geng et al., 2022). This provided a baseline to compare with patient's data and to assist the interpretation of potential divergent patterns indicating language reshaping/compensation in patients.

All participants were right-handed as assessed via the Edinburgh Handedness Inventory (Oldfield, 1971), had normal hearing and normal or corrected to normal vision. The study protocol was conducted in accordance to the Declaration of Helsinki for experiments involving humans, and approved by the Ethics Board of the Euskadi Committee and the Ethics and Scientific Committee of the BCBL (protocol code PI2020022). Informed consents were obtained from all participants involved in the study before the experiment.

2.2. Cognitive and linguistic assessment

A battery of standardized neuropsychological and linguistic tests was used to longitudinally evaluate participants on relevant linguistic and cognitive abilities. This battery included measures of general cognitive status as assessed via means of the 30-point screening Mini-Mental State Examination (MMSE) (Folstein, Folstein, & McHugh, 1975); verbal and non-verbal intelligence measured using the KBIT (Kaufman & Kaufman, 2013), and language production in Spanish and Basque via means of the BEST test (de Bruin, Carreiras, & Dunabeitia, 2017).

2.3. Picture-naming task

Language production was assessed using MULTIMAP, a multilingual picture-naming task for mapping eloquent areas during awake surgeries (Gisbert-Munoz et al., 2021). Briefly, MULTIMAP consists of an open access database of standardized color pictures representing both objects and actions. These images have been tested for relevant linguistic features in cross-language combinations including Spanish and Basque. Target words were matched on frequency, familiarity, number of orthographic neighbors, length and name agreement (i.e., higher than 80 %). Importantly, this task has been previously used to investigate the brain mechanisms underlying bilingual language production in neurotypical (Geng et al., 2022) and brain tumor populations (Quinones, Amoruso, Pomposo Gastelu, Gil-Robles, & Carreiras, 2021).

In separate blocks, participants were instructed to observe the pictures and name them overtly in Spanish or Basque as quickly and accurately as possible. Trials started with a fixation cross in the center of the screen lasting for 1 sec, followed by the picture displayed for 2 secs. ISI randomly varied between 3 and 4 secs. A total of 88 picture items (i.e., 44 for objects and 44 for actions) were used. Each picture was presented twice for a total of 176 trials per condition. Each block lasted ~ 15 min, and participants were allowed to take a short break between them. Above each object, we added the text "Esto es…" or "Hori da…" ("This is…" in Spanish and Basque, respectively) to force participants to produce a short sentence that agreed in number and gender with the target noun. In the case of the action pictures, we included a pronominal phrase to be used as the subject of the sentence, namely "El/Ella…" or "Hark…" ("He/She…" in Spanish and Basque, respectively). This introductory text cue was used to trigger the production of a sentence that began with the given subject and had a finite verb form in the third person singular. See Figure 2.

Participants' responses were recorded to estimate accuracy and naming latencies. We used MATLAB version 2012b and Cogent Toolbox (http://www.vislab.ucl.ac.uk/cogent.php) to present the images. Stimuli, Matlab script, and its compiled version are available at https://git.bcbl.eu/sgisbert/multimap2.

2.4. MEG and MRI data acquisition

MEG signals were recorded in a magnetically shielded room by means of a 360-channel Elekta -Neuromag system (360-channels, Helsinki, Finland). Signals were acquired continuously at a sampling rate of 1 kHz and online filtered between 0.1–330 Hz. Eye movements (EOG) were monitored using in a bipolar montage placed on the external chanti of each eye (horizontal EOG) and above and below the right eye (vertical EOG). Cardiac activity (ECG) was monitored as well by positioning an electrode below the right clavicle and another under the left rib bone.

Participant’s head position inside the helmet was tracked during the recording session with five head position indicator (HPI) coils. The location of each coil relative to standard anatomical fiducials (i.e., nasion, left, and right pre-auricular points) was defined with a 3D digitizer (Fastrak Polhemus, Colchester, VA). In addition, ∼300 points were digitalized over the scalp and eyes/nose contours to subsequently align the MEG sensor coordinates space to the participant’s T1 MRI.

All participants underwent an MRI session separated in time from the MEG session by at least two days in a 3T Siemens Magnetom Prisma Fit scanner (Siemens AG, Germany). High-resolution T1- and T2-weighted images were acquired with a 3D ultrafast gradient echo (MPRAGE) pulse sequence using a 64-channel head coil with the following acquisition parameters: FOV = 256; 160 contiguous axial slices; voxel resolution 1x1x1mm3; TR = 2530ms, TE = 2.36ms, flip angle = 7˚. For each patient, the origin of the T1/T2 weighted images (pre- and post-surgery) was set to the anterior commissure. Functional event-related scans consisting of 320 echo-planar images were acquired using a T2*-weighted gradient-echo pulse sequence with the following parameters: field of view: 192 mm; matrix = 64 x 64; echo time = 30ms; repetition time = 2 s; flip angle = 90 degrees. The volume was comprised of 33 axial slices with 3 mm isotropic voxels without slice gap. The first six volumes of each functional run were discarded to ensure steady-state tissue magnetization.

2.5. Lesion mapping

Lesions were manually drawn using the MRIcron software (Rorden, Karnath, & Bonilha, 2007) on the native space of participants' T1-weighted MPRAGE image by one of the neurosurgeons in charge of the patients' awake craniotomy (Garazi Bermudez). In addition, information from T2-weighted images was used when lesion boundaries were not clear in the T1. The lesion was then normalized to the MNI template and one of the authors (Ileana Quiñones) checked alignment between the delignated lesion and the lesion in the native space. A volume of interest (VOI) was created for each patient at each time point (i.e., pre- and post-surgery). Extent of resection (EOR; in cm3) was measured on postoperative imaging as: (Volume of (preoperative 3D Tumor Reconstruction ∩ postoperative Resection)*100/preoperative tumor volume).

2.6. Behavioural data analysis

Participant's vocal responses were recorded and monitored online by a research assistant during the task. An open-source in-house software ("SPONGE", available at https://github.com/Polina418/Audio_processing) was used to decode and convert the audio files into .wav format and semi-automatically detect speech onsets. Reaction times were measured as the interval between picture presentation and the onset of participant's verbal response. Erroneous responses or utterances containing disfluencies were excluded from the final analyses. Reaction times (RTs) and naming accuracies from individual patients were analyzed using Crawford-Howell (1998) frequentist *t*-tests for single-case analysis, and compared to the control group. This analysis was implemented on RStudio (Version 1.2.5019) using the psycho Package (Makowski, 2018).

2.7. MEG data preprocessing

Continuous MEG data were pre-processed off-line by means of the spatio-temporal signal space separation (tSSS) method (Taulu & Simola, 2006) implemented in Maxfilter 2.2 (Elekta-Neuromag) to subtract the external magnetic noise and correct for participants' head movements. Subsequent analyses were performed using the MatlabR_2014B (The MathWorks, Inc., Natick, Massachusetts, United States) and FieldTrip Toolbox [version

20170911] (Oostenveld, Fries, Maris, & Schoffelen, 2011). Recordings were down-sampled to 500 Hz and segmented into trials time-locked to picture onset, ranging from 500 ms before to 1000 ms after image onset. A semi-automatic procedure was used to remove trials containing electromyographic artifacts, SQUID jumps, and flat signals. Then, heartbeat and EOG artifacts were detected via means of a fast independent component analysis (FastICA) (Hyvarinen, 1999; Jung et al., 2000) and were linearly subtracted from the recordings. Across participants, the number of heartbeat and EOG components that were removed varied from 1–3 and 1–2 components, respectively.

2.8. MEG sensor-level analysis

Time-frequency representations (TFRs) were calculated on the clean MEG segments. Specifically, we focused on the beta band (13-28 Hz). This choice was methodologically motivated by previous findings from our group (Amoruso et al., 2021), showing that brain tumor patients show longitudinal language plasticity in this frequency band using a similar speech production task. TFRs were obtained using a Hanning tapers approach and a fixed window length of 500 ms, advancing in 10 ms steps, resulting in a 2 Hz frequency resolution. Power was separately estimated for each orthogonal direction of a gradiometer pair and further combined, for a total of 102 measurement sensors. Power was calculated as the relative change with respect to a ~500 ms pre-stimulus baseline. Statistical differences in spectral power between conditions were evaluated using cluster-based permutation tests (Maris & Oostenveld, 2007).

We averaged over frequency bins of interest (13-28 Hz; central frequency = 20.71 Hz) and tested a time-window from 100 ms to 600 ms after picture onset. This time-window was chosen based on methodological constraints imposed by the overt nature of the task, data inspection and neurophysiological evidence from previous studies using this picture naming task (Amoruso et al., 2021; Geng et al., 2022; Quinones et al., 2021), suggesting that recordings not contaminated with articulatory activity can be safely acquired around these time points. The permutation *p*-value was obtained with the Monte-Carlo method, using 1,000 random permutations. The alpha threshold for significance testing was a *p*-value below 5% (two-tailed).

2.9. Source activity estimation

Individual T1-weighted MRI images were segmented into the scalp, skull, and brain components using the Freesurfer software (Reuter et al. 2012). Co-registration between the MEG sensor space and participant's MRI coordinates was done by manually aligning the digitized points from the Polhemus to the outer scalp surface using the Neuromag tool MRIlab (Elekta Neuromag Oy, version 1.7.25). The lead field matrix was computed using the Boundary Element Method (BEM) model implemented in MNE suite (RRID: SCR_005972) (Gramfort et al., 2014), for three orthogonal tangential current dipoles, placed on a homogeneous 5-mm grid. The forward model was then reduced to the two principal components of the highest singular value for each source, corresponding to sources tangential to the skull. All sensors (i.e., gradiometers and magnetometers) were used for source estimation, normalizing the signal of each sensor by its noise variance considering a baseline period before picture onset. Cortical sources of the MEG signal were estimated using a Linearly Constrained Minimum Variance (LCMV) beamformer approach (Van Veen, van Drongelen, Yuchtman, & Suzuki, 1997). The covariance matrix used to derive beamformer weights was computed from the time-frequency window of the significant sensor-level effects and an equally sized baseline period prior to picture onset. To perform group-level analysis, brain maps were transformed from the individual MRIs to the standard Montreal Neurological Institute (MNI) by applying a nonlinear space transformation algorithm implemented in Statistical Parametric Mapping (SPM8, Wellcome Department of Cognitive Neurology).

Finally, statistical comparisons between conditions were performed with the location-comparison method (Bourguignon, Molinaro, & Wens, 2018), which has shown to be robust in dealing with spectral leakage problems. This method generates bootstrap group-averaged maps to build a permutation distribution of location difference between local maxima in the two conditions being compared and tests the null hypothesis that distance between them is zero. Local maxima are defined as sets of contiguous voxels displaying higher power than all other neighboring voxels. The threshold at $p < 0.05$ was estimated as the 95 percentile of the sample distribution. All supra-threshold local MEG peaks were interpreted as indicative of brain regions likely contributing to the sensor-level effects.

3. Results

3.1. Cognitive and linguistic results

Individual longitudinal changes in neurocognitive variables are shown in Figure 3. Results indicated that all patients preserved linguistic function in both languages after surgery as well as their cognitive status. Specifically, in the case of Spanish, all patients exhibited ceiling accuracy before and after surgery. For Basque, P2 and P4 performed better after surgery while patients P1 and P3 showed a marginal post-surgery decrease in accuracy. None of the patient's values significantly differed from the control group (Spanish mean value = 98%; Basque mean value = 89%) either before (all *p*s > 0.1) or after the surgery (all *p*s > 0.3), as indicated by Crawford *t*-tests. In the case of the MMSE, some patients obtained similar maximal scores across sessions (e.g., P2, P3 and P4), while P1 showed a marginal lower score after surgery. Nevertheless, across sessions, all patients scored between 30–27, which is considered the normal range when evaluating cognitive impairments.

Finally, for the KBIT, P1 and P2 exhibited identical scores across sessions, while patients P3 and P4 showed a considerable improvement after surgery.

3.2. Behavioral results

Table 2 shows mean accuracy and reaction time values (RT) for each patient, as well as *p*-values for the Crawford-Howell *t*-tests comparing individual patients against the control group. Overall, no significant differences were observed in accuracy and RTs, which speaks in favor of successful language compensation. Only P2 showed a significant lower performance in naming accuracy for actions in Basque after surgery. Nevertheless, his performance was still very good (i.e., ~92%).

3.2. MEG results

The longitudinal contrasts (post vs. pre-surgery) performed for each naming condition (objects and actions) and language (Spanish and Basque) in the beta frequency band (13-28 Hz) showed specific significant effects for actions in both languages (all Monte Carlo *p*s = 0.002, two tailed). No significant differences were observed for the object naming condition (all Monte Carlo *p*s > 0.45, two tailed). Figure 4A shows time-resolved spectra of the action naming longitudinal contrast for each language. In the case of Spanish, beta power modulations across sessions were highlighted by a positive cluster between ~310-500 ms in left middle-frontal sensors. In the case of Basque, the positive cluster was evident between ~180-600 ms and comprised left frontal sensors and right fronto-parietal ones. Source localization results (Fig. 4B) indicated that the longitudinal action effect for Spanish mainly originated in premotor and inferior frontal regions of the left hemisphere. The same effect in Basque, showed a similar involvement of left premotor cortex but with the additional recruitment of parietal and premotor regions in the right hemisphere.

Overall, in line with previous evidence for a similar longitudinal contrast in patients with dorsal gliomas (Amoruso et al., 2021), we observed beta power increases after the surgery along with preserved cognitive and linguistic abilities. Importantly, the direction of the action post- vs.

pre-surgery effect was consistent at the individual patient's level, namely all patients showed stronger beta power increases after tumor removal.

Then, we reused MEG data from a previous study (Geng et al., 2022) in which a group of healthy highly proficient bilinguals (n = 16) performed the same picture-naming task and estimated beta networks involved in action naming for Spanish and Basque, to better understand patterns of potential reshaping in patients. Healthy controls showed similar negative clusters in the beta band (13-28 Hz) for action naming vs. baseline in Spanish (between ~180-500 ms) and Basque (between ~300-500 ms) over bilateral posterior, left parieto-temporal and frontal sensors (all Monte Carlo ps = 0.004, two-tailed). See Figure 5. This effect mainly originated in a left-lateralized network comprising superior parietal, premotor and inferior frontal regions, as well as bilateral visual associative areas. Importantly, the contrast between languages did not yield significance, suggesting that action knowledge is similarly processed in the healthy bilingual brain.

Contrariwise, a significant language effect (Spanish vs. Basque; Monte Carlo p-value = 0.002, two tailed) was observed for action naming in the group of patients after the surgery. This effect was highlighted by a negative cluster in right parieto-temporal sensors, showing less beta power (13-28 Hz) for Spanish as compared to Basque between ~390-600 ms (see Fig.6A). Source localization results indicated that the post-surgery language effect originated in parietal, superior temporal and prefrontal regions of the right hemisphere (see Fig. 6B). No significant language differences were observed for action naming prior to the surgery. In addition, no significant differences were observed for either pre- or post-surgery sessions in the case of objects (all Monte Carlo ps > 0.12, two tailed).

Overall, the finding of a significant language effect over right sensors after surgery is in contrast with the results of the control group, for whom no significant differences across languages were observed. This may suggest that while comparable adaptive compensation for processing action knowledge is present across languages before surgery (i.e., indicating language-invariant semantic processing similar to controls); tumor removal can prompt out different patterns of functional reorganization in the L1 and L2.

4. Discussion

In the present study, we focused on highly proficient Spanish-Basque bilinguals harboring brain tumors in dorsal frontoparietal nodes to investigate (i) whether compensatory longitudinal changes in beta rhythms (13-28 Hz) specifically target action naming and, more critical to our hypothesis, (ii) whether this compensation similarly stands across the two languages a bilingual patient speaks. In keeping with previous findings, we replicated the existence of longitudinal compensation in the beta band, reflected in power increases along with preserved behavioral performance in picture naming. As expected, this oscillatory effect was specifically observed for the action naming condition and was present in both Spanish and Basque, thus supporting the engagement of the dorsal stream in the semantic retrieval/representation of action knowledge across languages. Another critical finding emerged when contrasting action naming between a group of healthy bilinguals and the group of patients (separately within pre- and post-surgery sessions). Prior to the surgery, healthy controls and patients showed no differences across languages, likely indicating language-invariant semantic processing across L1-L2. However, after the surgery, patients exhibited beta power differences between Spanish and Basque in the right hemisphere, suggesting that tumor removal triggered a differential reorganization of the L1 and the L2.

4.1. Lexico-semantic compensation of action naming in bilingual patients with dorsal gliomas

Previous evidence indicates that the semantic processing of object and action knowledge can be partially dissociated in ventral and dorsal functional networks, respectively (Gleichgerrcht et al., 2016; Kemmerer, 2014; Shapiro et al., 2006; Shapiro et al., 2005). Furthermore, this category-based segregation has been also reported in bilingual speakers (Consonni et al., 2013; Geng et al., 2022; Willms et al., 2011), suggesting the existence of semantic language-invariant systems across L1-L2 supporting object/action dissociations. In line with this evidence, we show that frontoparietal regions in the dorsal stream are critical for processing action-related meaning across the two languages a bilingual speaks and that the resection of tumors affecting dorsal areas lead to a selective compensation for the lexico-semantic processing of action material. Furthermore, we show that this compensation is successful in preserving action naming in L1 and L2, giving the absence of severe production impairments across languages either before or after the surgery.

These findings raise the question of which neuroplasticity mechanisms may have favored language preservation. It has been shown that gliomas can alter functional connectomics profiles and affect global network communication (Cargnelutti, Ius, Skrap, & Tomasino, 2020; Duffau, 2020). In this context, different compensatory strategies can be called into play, including the recruitment of peritumoral tissue, the engagement of secondary ipsilateral regions functionally connected to areas close to the tumor (or its cavity) as well as contralateral homologues, typically in the right hemisphere (Duffau, 2005, 2020; Duffau et al., 2003). Furthermore, plasticity can be seen as a multistage process, firstly occurring preoperatively due to tumor growth and secondly, postoperatively, with reorganization triggered by the surgical trauma itself. Indeed, preoperative plasticity can be damaged during the surgery, and thus a subsequent development and/or reinforcement of reshaping mechanisms is necessary to explain patient's recovery after the intervention (Duffau et al., 2003; Robles, Gatignol, Lehericy, & Duffau, 2008).

In the present study, we focused on this latter aspect, namely the functional compensation resulting from tumor removal as compared to its presence before surgery. In keeping with previous findings (Amoruso et al., 2021), longitudinal compensation was indexed by post-surgery power increases in the beta band (13–28 Hz). This effect was true for both Spanish and Basque and consistent at the individual patient's level.

Beta rhythms are one of the most intriguing oscillations in the brain, supporting a wide range of cognitive functions. So far, several accounts have been advanced to explain their mechanistic role in humans. From a general standpoint, beta synchronization has been associated to network dynamics involved in the (re)activation of cortical representations (Spitzer & Haegens, 2017). Similarly, in the language domain, Weiss and Mueller (2012) have proposed that beta enhancement serves to bind distributed sets of neurons into a meaningful representation of memorized contents. Briefly, according to the authors, this will explain how the brain integrates information processed at different timescales and in separate neural regions in order to produce/understand a coherent speech unit. Interestingly, a critical aspect that both views underscore is the role of beta rhythms in facilitating functional networking in the brain. This aligns well with computational frameworks (Kopell, Ermentrout, Whittington, & Traub, 2000; Sherman et al., 2016), suggesting that beta oscillations can synchronize at long conduction delays, enabling high-level interactions between spatially distant brain areas. This property becomes even more critical when considering that functional reshaping triggered by gliomas can affect network-level communication and potentially involve the compensatory recruitment of remote areas in the contralateral hemisphere. This aspect makes beta a plausible candidate to support reallocation of linguistic functions and is consistent with neurophysiological evidence from stroke and brain tumor patients (Kielar, Deschamps, Jokel, & Meltzer, 2016;

Piai, Meyer, Dronkers, & Knight, 2017; Traut et al., 2019) showing a shift of language processing to the right hemisphere mediated by low frequency bands, including beta.

While our study mainly focused on beta rhythms, we acknowledge that other oscillatory changes may have occurred in response to the surgery. For instance, recent evidence indicates that bilingual patients with left LGGs can exhibit a rightward shift of parietal alpha (8-12 Hz) oscillations specifically related to L2 processing (Quinones et al., 2021). This effect could indicate the presence of different cognitive demands when processing L2 representations. Indeed, previous studies have linked right parietal alpha activity to increased load during cognitive control (Obleser, Wostmann, Hellbernd, Wilsch, & Maess, 2012) and, in particular, to language control in bilinguals (Bice, Yamasaki, & Prat, 2020; Tao, Wang, Zhu, & Cai, 2021).

4.2. Postoperative differences in L1 and L2 reshaping in bilingual patients

Nevertheless, it is worth noting that even though beta effects were present in both languages, longitudinal patterns for Spanish and Basque differed in terms of timing, scalp and source location. Indeed, while Spanish showed a left lateralized effect in premotor and inferior frontal regions, Basque additionally engaged right-hemisphere sources. To better understand this differential pattern, we contrasted action naming between Spanish and Basque separately before and after surgery. The same analysis was paralleled in a group of healthy Spanish-Basque bilinguals to assist the interpretation of potential divergent patterns in patients.

Prior to the surgery, action naming in Spanish and Basque did not differ, indicating comparable adaptive compensation for accessing action-based knowledge across languages. This finding was further supported by data from controls showing overlapping oscillatory beta networks in Spanish and Basque during action naming, likely indicating converging lexico-semantic processing in L1 and L2. However, after the surgery, differences between languages became evident. On the one hand, Basque showed higher activity in right parietal, superior temporal and prefrontal regions contralateral to the tumor's cavity. Importantly, this rightward activation was not present in healthy controls during action naming, suggesting that this set of regions was secondary engaged to achieve accurate lexico-semantic processing of action knowledge in the L2 once the tumor was resected. This is in keeping with previous findings from our lab (Quinones et al., 2021) combining fMRI and MEG techniques to map language lateralization in bilingual brain tumor patients and showing a stronger shift of activity toward the right hemisphere for Basque as compared to Spanish after surgery.

On the other hand, no recruitment of the right hemisphere was observed for Spanish, which instead showed more local changes in ipsilateral areas similarly recruited by controls during action naming. Such an oscillatory pattern likely reflects the re-weighting of functional connections between preserved healthy regions, implying that during postoperative recovery, some of these areas become more active to support adaptive compensation (York & Steinberg, 2011).

It has been proposed that plasticity mechanisms follow a hierarchical organization in which the recruitment of the contralesional hemisphere occurs at later stages, when other neural resources (e.g., recruitment of perilesional tissue and/or ipsilesional areas) have been depleted. Yet, the postoperative involvement of the right hemisphere occurred quite early in the case of Basque (i.e., within the ~3 months following surgery; see also Quiñones et al., 2021 for a similar finding). While there is evidence showing that contralateral plasticity can be very quickly engaged (Duffau et al., 2003), this still leaves open the question of why this compensatory pattern was specifically observed for the L2.

Previous evidence (Gatignol, Duffau, Capelle, & Plaza, 2009) indicates that L1 and L2 can follow different postoperative trajectories in glioma patients, probably due to experiential factors such as AoA, language's proficiency and frequency of use. For example, it has been hypothesized that the order of postoperative language recovery mirrors the order of language acquisition (Emmorey & McCullough, 2009; Galloway, 1978). In our study, all bilinguals but one (patient 3) acquired Basque later than Spanish. It could be that the language acquired earlier is more robustly represented in the brain and thus more easily compensated; while the one acquired later may necessitates from the additional recruitment of contralateral homologues —which can promote language recovery during the acute phase (Saur et al., 2006).

An alternative, although not mutually exclusive interpretation, is that language proficiency might have also played a role. Even though all patients were balanced highly proficient bilinguals, they all reported Spanish as being their L1. The engagement of control regions in the right prefrontal cortex supports this view, suggesting that action naming in Basque may have deployed more cognitive resources, in terms of language control (Hernandez et al., 2001) and semantic monitoring (Shen, Fiori-Duharcourt, & Isel, 2016), than Spanish. This further indicates that reconfigurations preserving semantic processing after surgery may involve the additional engagement and/or changes in the interactions with other networks (i.e., executive control network).

Additionally, the "frequency hypothesis" posits that, in cases of brain damage, the language that is used more frequently before the illness and is more stimulated afterwards is better preserved and will recover better (Gatignol et al., 2009). However, in this study, most of the patients used both languages to an equal degree before and after surgery, which makes it unlikely for this hypothesis to account for the observed results.

An important aspect to stress is that even Spanish and Basque differed in terms of their oscillatory patterns after tumor removal, naming performance was well preserved in both languages, indicating successful postoperative reorganization - albeit supported by different compensatory strategies - rather than differential L1 vs. L2 deficits (Quinones et al., 2021).

We can further speculate, based on evidence from intraoperative cortical mapping in bilinguals (Giussani, Roux, Lubrano, Gaini, & Bello, 2007), that while there is a common pattern of L1-

L2 organization in gross anatomical regions; more subtle, distinct microanatomical systems can be localized within these regions for each language (Paradis, 2004). Therefore, the functional connections among the Spanish and Basque microanatomical systems could have been differently impacted by the surgical trauma, resulting in unique postoperative compensation patterns for each language. Indeed, it has been suggested that variability in network(s) reconfiguration is higher after than before tumor resection (Duffau, 2020).

As a final note, it is worth mentioning that gliomas typically show recurrence patterns in the long-term follow-up after initial resection (Ferracci, Michaud, & Duffau, 2019). Additionally, in many cases, tumor resection cannot be total due to the existence of residual functionality in the area infiltrated by the tumor, as it was the case for one of the patients participating in the present study. Thus, a multistage approach in which successive reoperations take place is counseled (Robles et al., 2008), given it favors plasticity and further functional reallocation away from the tumoral region. In this context, our findings of distinct L1 and L2 plasticity patterns following an initial brain surgery (e.g., the differential recruitment of the contralateral unaffected hemisphere) can be informative to plan follow-up strategies, as it has been shown that when decreased ipsi-lesional engagement is compensated with increased contra-lesional one, subsequent reoperations can be facilitated (Duffau, 2020).

4.3. Limitations and avenues for further research

Our study is not without limitations. First, while we acknowledge that an obvious limitation of our study is the small sample size (*n* = 4), it is important to note that: (i) it is quite challenging to access this type of population (i.e., highly proficient bilinguals with left dorsal gliomas) and obtain pre- and post-surgery measures within the same individuals; (ii) longitudinal designs, like the one employed here allow each patient to be his/her own control across sessions, thus reducing the confounding effect of inter-individual variability and increasing statistical power

(Zeger & Liang, 1992); (iii) appropriate Crawford *t*-tests were used to analyze data while preserving the unique patterns of each individual patient; lastly (iv) the longitudinal oscillatory effects found in the present study are remarkably robust at the individual patient's level (e.g., all patients show the same direction of the effect). While these aspects contribute to the scientific rigor of our findings, future studies are needed to investigate whether they can be replicated in larger samples.

Another potential drawback of this study is that participants were highly proficient bilinguals, so it is uncertain whether the longitudinal patterns observed here would be similar (or not) in individuals with other types of bilingual experience (e.g., less proficient or immersed bilinguals). This is an important consideration for future research as it can provide a more comprehensive understanding of whether changes in beta power can be generalized to other type of bilingual populations.

Finally, our search of neural plasticity indices was circumscribed to functional compensation, overlooking changes in subcortical structures which are critical in supporting reshaping at the cortical level. For instance, dorsal fronto-parietal hubs are known to be subcortically connected by the superior longitudinal fasciculus (SLF) (Kamali, Flanders, Brody, Hunter, & Hasan, 2014; Makris et al., 2005). In a previous study (Amoruso et al., 2021) testing Spanish monolingual patients harboring LGGs in the left dorsal pathway, we found that post-surgery beta power increases in the right hemisphere correlated with volume increases in the right SLF, suggesting that functional and structural plasticity are closely intertwined. Therefore, a potential area of research that could provide a deeper understanding into the mechanisms of brain plasticity in bilinguals would be investigating the microstructural (e.g. FA) and macrostructural properties (e.g. volume changes) of relevant white matter bundles, and how they may be linked to functional changes.*4.4. Conclusions*

Overall, we replicate previous findings supporting a key role of beta oscillations as a signature of language compensation in brain tumor patients and, more importantly, we extend it to the bilingual population. Furthermore, we show that bilingual patients with dorsal gliomas exhibit a selective compensation for action naming in their L1 and L2, providing evidence for the specific involvement of frontoparietal regions in the semantic retrieval/representation of action knowledge across languages. Finally, we show that while prior to the surgery, L1 and L2 can follow a similar reorganization profile; postoperative reshaping triggered by tumor removal leads to divergent reconfiguration patterns within each language. Taken together, these findings provide new insights into the spectro-temporal dynamics supporting postoperative recovery in the bilingual brain, and the potential roles that disruption of preoperative plasticity triggered by surgical trauma and/or language proficiency may have on this process. Beyond theoretical implications, our results provide valuable clinical information to plan multistage surgical strategies tailored to patients' differential neuroplasticity for each language. Such a strategy can improve EOR in follow-up surgeries while fully preserving all the languages a patient speaks.

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Table Legends

Table 1. Patient's demographics, linguistic and clinical characteristics

Table 2. Comparison of individual patient scores to control group performance during naming in Spanish and Basque. Mean (M) and *p*-values from Crawford-Howell *t*-tests comparing accuracy and reaction times (RT) during object and action naming in both languages before and after surgery for tumor resection.

Figure Legends

Figure 1. Lesion delineation for individual patients.

Figure 2. Examples of object and action stimuli and experimental task. In separate blocks, participants were requested to observe the pictures and overtly name them in either Spanish or Basque as quickly and accurately as possible. Production of nouns and verbs was requested in the context of short sentences, which is a more ecological form of speech than isolated naming.

Each trial began with a fixation cross on the screen for 1 second followed by the picture presented for 2 seconds. ISI randomly varied between 3-4 secs.

Figure 3. Patient's cognitive and linguistic performance before and after surgery. Charts showing individual patients' scores for the pre- and post-surgery screening of cognitive status (i.e., Minimental Cognitive State Examination [MMSE], verbal and non-verbal intelligence (KBIT) and language production in Spanish and Basque (BEST).

Figure 4. Longitudinal effect in patients for action naming. Panel A shows time-resolved spectra of the longitudinal action naming effect (post vs. pre) in Spanish (top left) and Basque (bottom left), together with the positive clusters in the beta frequency band (13-28 Hz), indicating power increases after surgery. Line charts show individual patients' mean beta power at each session (before and after tumor resection), averaged over sensors associated with the clusters. Mean beta values are also shown for healthy bilingual controls as indicated by black dotted lines (*n* =16; Spanish = -0.538, Basque = -0.456). Panel B shows source localization of the longitudinal action naming effect in each language, circumscribed to the time interval highlighted by the clusters. All plotted regions reached a *p*-value < 0.01.

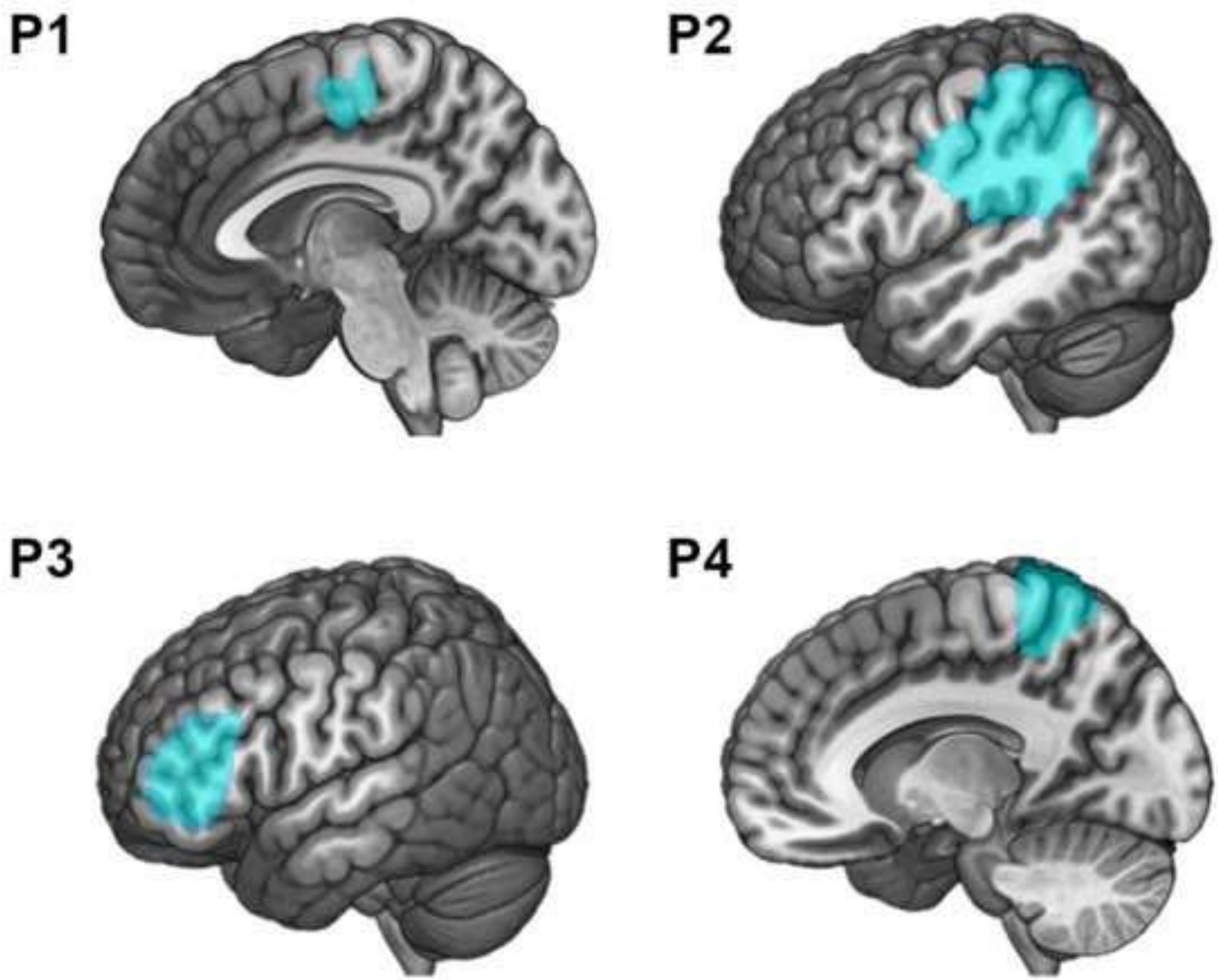
Figure 5. Action naming in healthy bilingual controls. Panel A shows the negative cluster in the beta frequency band (13-28 Hz), indicating lower beta power for naming as compared to baseline, together with the action naming network resulting from the source level analysis. Panel B shows the negative beta cluster corresponding to the same action naming effect is Basque and the resulting network of areas underscored by the source level analysis. In both

cases, source localization of the effect is circumscribed to the time intervals highlighted by the clusters. All plotted regions reached a *p*-value < 0.01.

Figure 6. Language effect in patients after surgery. Panel A shows time-resolved spectra of the language contrast (Spanish vs. Basque) after tumor resection, together with the negative cluster in the beta frequency band (13-28 Hz), indicating lower beta power for Spanish. Line charts show individual patients' mean beta power for each language, averaged over sensors associated with the cluster. Mean beta values are also shown for healthy bilingual controls as indicated by the blue dotted line (*n* =16; Spanish = -0.39, Basque = -0.551). Panel B shows source localization of the language effect, circumscribed to the time interval highlighted by the significant cluster. All plotted regions reached a *p*-value < 0.01.

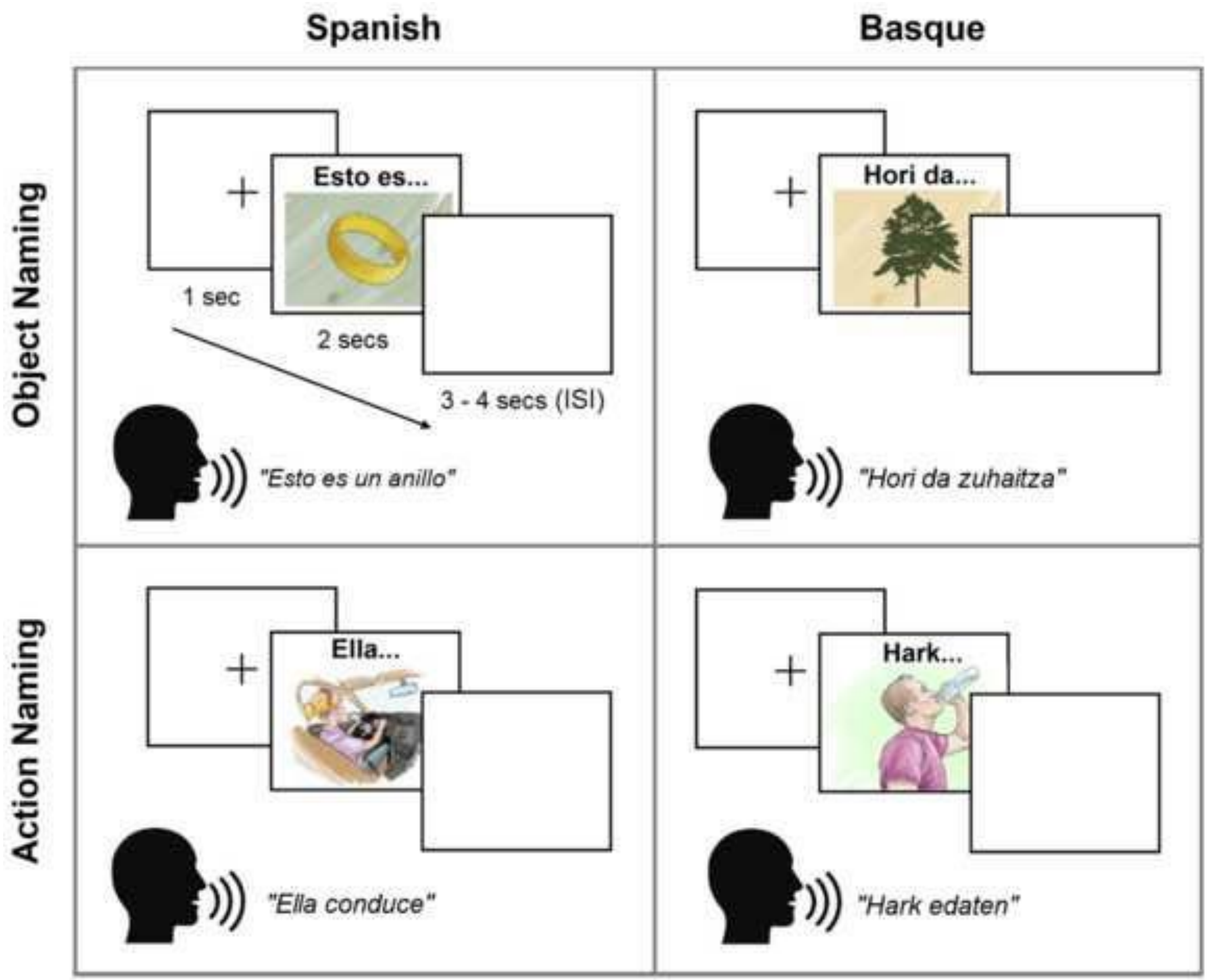
	Age	Sex	Educ. (years)	Occupation	L1	L1 AoA	L2	L2 AoA	L1/L2 % of use	Tumor Location	Tumor Volume (cm^3)	EOR (%)
P1	45	F	14	Businesswoman	Spanish	0	Basque	5	50/50	Motor	23.00	76
P2	47	M	20	Aircraft pilot	Spanish	0	Basque	3	95/5	Parietal	87.83	100
P3	56	M	12	Mechanic	Spanish	0	Basque	0	40/60	Frontal	28.68	100
P4	41	M	20	Administrator	Spanish	0	Basque	3	50/50	Parietal	18.29	100

	Pre-surgery				**Post-surgery**			
	Object		Action		Object		Action	
	Mean	***p*-value**	**Mean**	***p*-value**	**Mean**	***p*-value**	**Mean**	***p*-value**
Accuracy								
Spanish								
P1	100	0.72	99.43	0.77	99.4	0.9	99.43	0.77
P2	100	0.72	100	0.58	100	0.72	100	0.58
P3	97.4	0.5	98.7	0.97	100	0.72	100	0.58
P4	98	0.66	100	0.58	100	0.72	100	0.58
Basque								
P1	99.43	0.82	97.74	0.73	99.4	0.83	99.43	0.68
P2	100	0.62	100	0.5	98.7	0.9	**92.59**	**0.01***
P3	95.65	0.13	100	0.5	100	0.62	98.14	0.87
P4	96.15	0.2	100	0.5	95.34	0.10	100	0.5
RT								
Spanish								
P1	759.9	0.61	897.49	0.64	718.93	0.55	940.6	0.7
P2	868.91	0.78	890.12	0.63	789.25	0.65	882.57	0.61
P3	1009.54	0.98	1209.73	0.84	776.40	0.63	1159.44	0.92
P4	851.7	0.75	1054.56	0.89	981.98	0.96	1113.32	0.99
Basque								
P1	816.41	0.75	1018.07	0.79	881.95	0.86	1075.67	0.89
P2	954.48	0.98	1056.9	0.86	671.65	0.52	789.11	0.45
P3	965.91	0.99	1044.98	0.84	771.97	0.67	1045.46	0.84
P4	856.81	0.81	890.97	0.59	914.55	0.91	1133.53	0.99


P1
P2
P3
P4

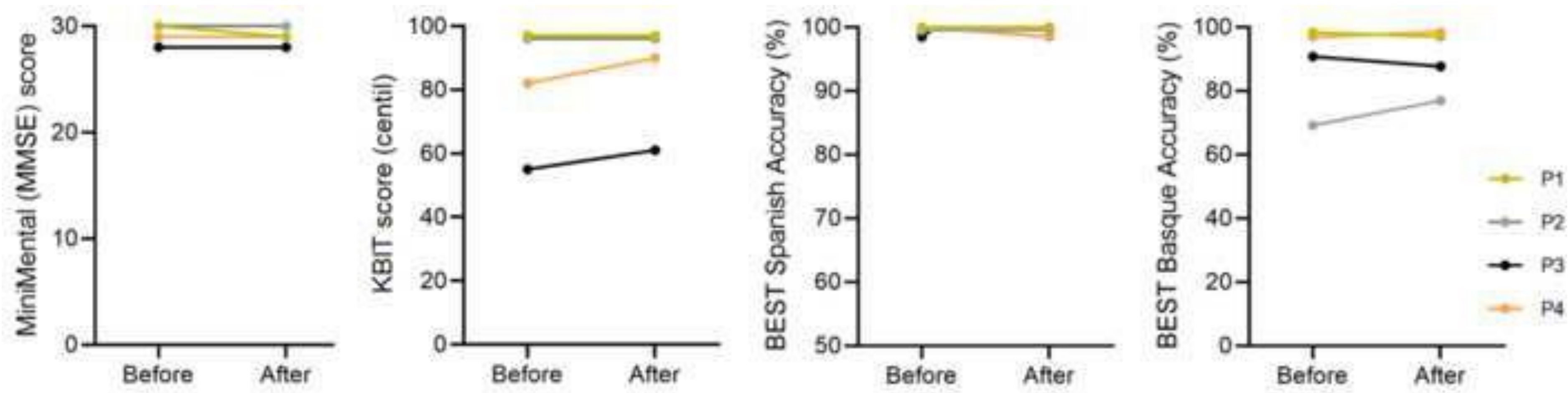
Figure

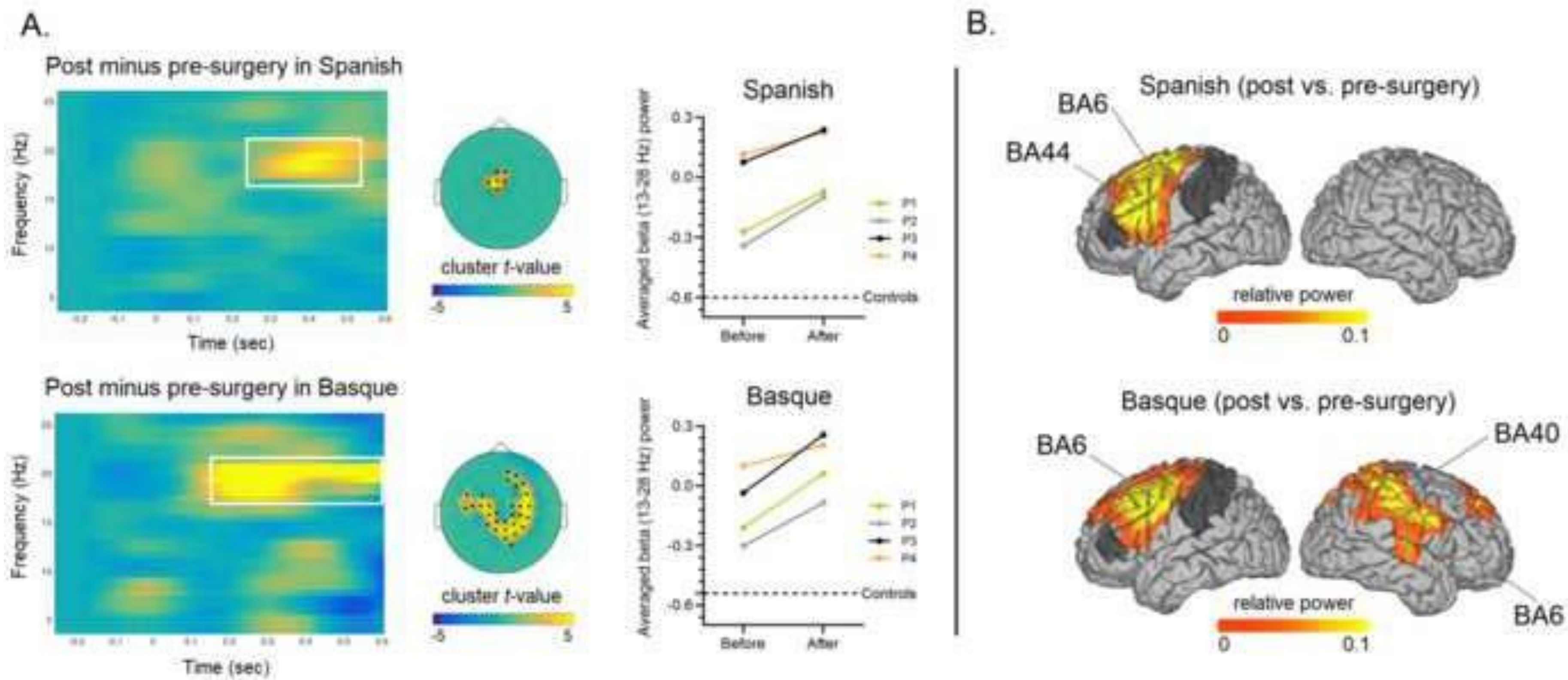
Click here to access/download;Figure;Figure 2.tif



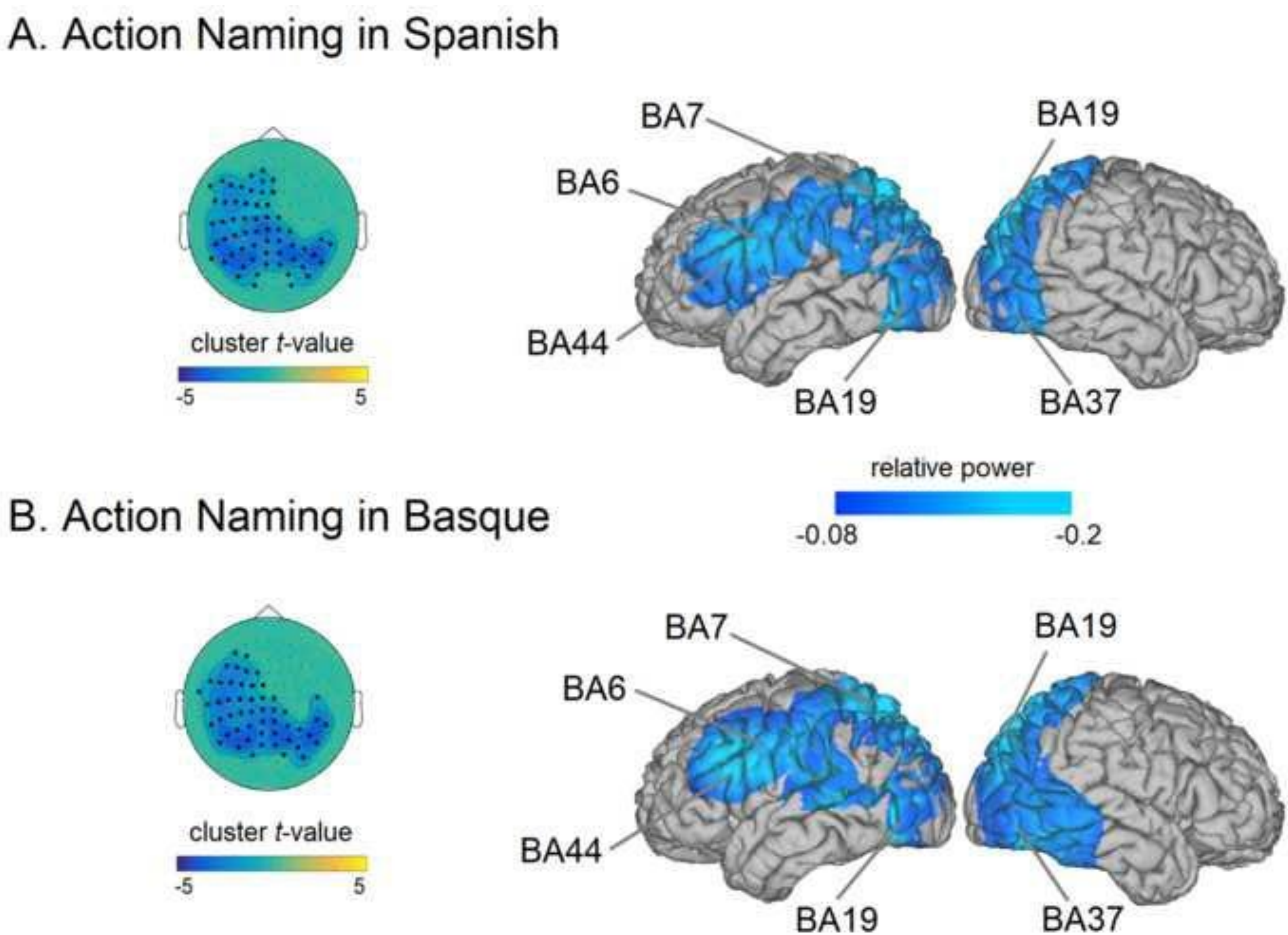
Figure

Click here to access/download;Figure;Figure 3.tif





A.
Post minus pre-surgery in Spanish
Frequency (Hz)
Time (sec)
cluster t-value
-5
5
Spanish
Averaged beta (13-28 Hz) power
0.3
0.0
-0.3
-0.6
Controls
Before
After
P1
P2
P3
P4
Post minus pre-surgery in Basque
Basque
B.
Spanish (post vs. pre-surgery)
BA6
BA44
relative power
0
0.1
Basque (post vs. pre-surgery)
BA40


A. Action Naming in Spanish
cluster t-value
-5
5
BA7
BA6
BA44
BA19
BA19
BA37
relative power
-0.08
-0.2
B. Action Naming in Basque
cluster t-value
-5
5
BA7
BA6
BA44
BA19
BA19
BA37


A.
Spanish minus Basque post-surgery
Frequency (Hz)
Time (secs)
cluster t-value
-5
5
Action naming post-surgery
Averaged beta (13-28 Hz) power
0.6
0.3
0.0
-0.3
-0.6
Spanish
Basque
P1
P2
P3
P4
Controls
B.
Spanish vs. Basque (Post-surgery)
BA 40
BA 46
BA 22
relative power
-0.02
-0.1