Measuring intracortical responses during word production

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ABSTRACT.

Intracranial electroencephalography (iEEG) is an invasive technique that enables direct recording of neural activity in the human brain. iEEG is only possible under clinical circumstances where identification of epileptic seizure origin is needed. Intracranial recordings also can help determine spatial and temporal neural dynamics occurring during speech production. The present study was a pilot experiment, where we could test the viability of word production experiments by using intracortical measurements in epileptic patients. Specifically, we investigated intracranial Evoked Event-Related Potentials iERPs in five participants performing an overt picture naming task. We found task-related activity in Broca's area, along the left temporal cortex and in the anterior occipital lobe. Our results demonstrate that our assessment setting was experimentally viable and could potentially elucidate the neurophysiology of language processing.

KEY WORDS.

iEEG, intracranial recordings, speech processing, word production, iERP.

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CONTENTS.

INTRODUCTION.

The neural representation of speech production is an emerging area of investigation in the study of human language. For many years, the predominant approach was brain mapping the activation patterns that correlated with word production tasks. The development of a broader spectrum of measurement and analysis techniques has opened a new way to gather information regarding the spatiotemporal dynamics of word production.

Direct electrophysiological recordings from the human brain have been possible thanks to the development of intracranial electroencephalography (iEEG). This technique is usually employed in pharmacologically resistant epileptic patients (Serletis et al., 2014) who require mapping before surgery. To ascertain the epileptic seizure onset, electrodes are placed within the brain and patients are continuously monitored for several days. Beyond the clinical purposes of this technique, iEEG represents a unique opportunity to record neural activity while patients perform different cognitive tasks. Therefore, it provides a rare opportunity to investigate the neural correlates of language. Unlike traditional scalp electroencephalography (EEG), iEEG provides direct access to neural population activity in theoretically important cortical regions located on the brain's ventral surface (Sperling, 1997). Additionally, iEEG offers improved spatial and temporal resolution and the possibility to record directly the activity of single neurons (Rey et al., 2014). Moreover, it provides increased signal to noise ratio, and also avoids muscle artefacts, such as eye movements.

iEEG has been used to investigate the neural bases of several cognitive processes, yet relatively few studies have been published in the domain of language processing. One of the most remarkable is the one conducted by Sahin et al. (2009). These authors investigated the spatio-temporal dynamics of lexical, grammatical and phonological components of the linguistic computational processing. They reported that these components can be separated in time and space at a neural circuit level within Broca's area. As shown in this paper, this technique offers a unique opportunity to study the time course of language production. Partially inspired by these findings we conducted experiments with this methodology in the field of language production.

In collaboration with IMIM-Hospital del Mar Epilepsy Unit, the main goal of this project was to implement an evaluation setting for cognitive research in order to assess the language processing in epilepsy patients by using iEEG. This project was developed in two steps: The first phase was to define a comprehensive experimental protocol to gather new knowledge about neural circuits sustaining language production and the role of executive control processes on it. Ten tasks were designed for this purpose. The second phase aimed to implement the protocol. On this stage of the project, we collected intracranial recordings data from 10 different tasks in 5 participants while they remained hospitalized.

To achieve our goal, one of our specific objectives was to describe the time course of word production during overt picture naming. We based our hypothesis in the spatiotemporal model of word production presented in Levelt, Roelofs & Meyer (1999). This model conceives that word production is a process of successive steps which starts with lexical selection and ends with the initiation of the word articulation. Each computational stage of the process would explain the different representations involved and its evolution over time. Taking this into account, we wanted to identify in iERPs the temporal information underlying word retrieval.

The time course of word production.

One of the most remarkable characteristics of speaking and listening is the speed at which it occurs. Speakers produce easily between 2 and 5 words per second (Hagoort et al., 2014), so information must be decoded by the listener within roughly the same time frame. With this in mind, the time course of the underlying processes becomes crucial to understand the speech production.

The spatiotemporal model of word production (Levelt et al., 1999) is not only capable of predicting the time window in which the activation takes place, but also is suitable to measure the modulatory effects of psycholinguistic variables on the activation of specific brain regions at a specific time. Based on this theory, many studies have attempted to relate the functional components of word production, such as lexical selection and phonological code retrieval, to different brain regions.

By recording neural activity using iEEG, it has been demonstrated that lexical, grammatical and phonological information is processed sequentially in Broca's area in specific time windows (Sahin et al., 2009; Edwards et al., 2010). Similar electromagnetic studies have offered information regarding the neural correlates and the time course of word production (Salmelin et al., 1994; Turennout et al., 1998; Schmitt et al., 2000; Rahman and Sommer, 2003; Costa et al., 2009). However, despite the good correlation among results obtained with different techniques, there is still controversy about the precise time course of brain activation during tasks which involve word production such as picture naming.

One popular model that tried to ‘estimate’ the time course of the different language components involved in word production, has been proposed by Indefrey and Levelt (2004; 2011). This model provides the following time windows (in milliseconds) during which different regions are activated in picture naming: conceptual preparation (from picture onset to selection of target concept) at ~175 ms, then lemma retrieval at ~250 ms, phonological code retrieval at ~330 ms, syllabification at ~455 ms and phonetic encoding (till onset of articulation) at ~600 ms.

A similar approach was presented by Miozzo et al. (2014). They postulate that once the stimulus is presented, it breaks out a serial succession of processing stages. First, semantic processing at ~150 ms, primarily involving activation in left posterior temporal–anterior occipital areas. Followed by word form processing at ~200 ms, recruiting the left posterior superior and middle temporal gyrus (but probably also the left anterior insula and the right supplementary motor area). And finally, an activation in premotor/precentral cortex and inferior frontal gyrus (IFG) at ~400 ms, consistent with past findings (Marinkovic et al., 2003; Gaillard, 2006; Costa et al., 2009).

Beside these proposals which have attempted to define the time course of word production, some other researchers have investigated the modulatory effects of some linguistic variables on the neural dynamic of speech production. Among these variables, word frequency has been used to study lexical retrieval and its temporal time course (Strijkers et al., 2010; Brysbaert et al., 2015). Behaviourally, word frequency affects the speed and accuracy with which picture naming is performed. Specifically, pictures with high-frequency names tend to be named faster and more accurately than pictures with low-frequency names (Oldfield and Wingfield, 1965; Dell, 1990; Jescheniak and Levelt, 1994; Navarrete et al., 2006; Almeida et al., 2007). Similarly, it has been proposed that this behavioural evidence would be an index of lexical retrieval at a neural level. Indeed, both Sahin et al. (2009) and Strijkers et al. (2010), found that there is a modulation of the electrophysiological responses at about 200 ms after the stimulus presentation when participants name pictures with high-frequency names versus low-frequency names (see figure 1).

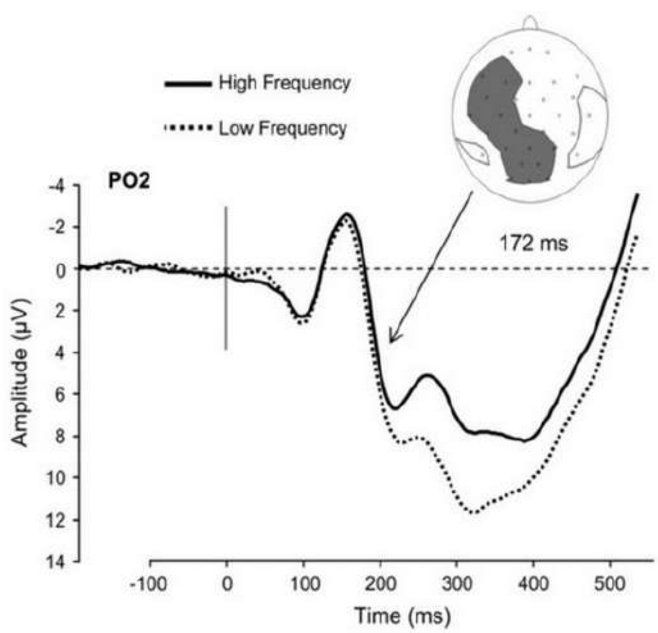

Figure 1. Low-frequency ERPs compared with high-frequency ERPs in Experiment 1 at PO2 and topographic distribution of electrodes showing a significant effect at 172 ms after picture presentation (gray area) (Figure taken from Strijkers et al., 2009).

METHODS.

Participants.

Five patients (3 men/2 women, right-handed, mean age 41±4.7 years-old) with pharmacoresistant focal Temporal Lobe Epilepsy, volunteered to participate in this research study. Participants were inpatients under clinical care of the IMIM-Hospital del Mar Epilepsy Unit. All were candidates for selective surgical treatment due to their non-tractable epilepsy. Depth electrodes were implanted in each patient's brain in order to determine the seizure onset region. The location of the electrodes were established purely on clinical reasons. Participants were selected under a restrictive criteria (for more details see 'Patients and Selection Criteria' in Appendix 1). All underwent an extensive neuropsychological evaluation, were Catalan-Spanish bilingual speakers, had primary to high academic level and normal or corrected-to-normal vision (for more details see 'Patient Information' in Table 1, Appendix 1). Since the study aims to study language production under normal circumstances, patients were assessed in absence of pharmacological treatment.

Ethics Statement.

As anticipated in the introduction, this study is part of an extensive research protocol about the neural basis of language representation, access and control. The study was approved by The Clinical Research Ethical Committee of the Municipal Institute of Health Care (CEIC-IMAS). According to the Declaration of Helsinki, participants were informed about the procedure and they gave their written consent before the experiment.

Experimental Design and Materials.

Two of the ten tasks which are part of the protocol were selected:

A. Experiment 1: Picture Naming Task I

Ninety-six drawings of familiar objects from a wide range of semantic categories were selected. Two independent variables were manipulated: *Lexical Frequency* of the picture names and *Visual Complexity*. Half of the pictures were classified as high-frequency words (lemma frequency average 42.38), and half as low-frequency words (lemma frequency average 3.69) [LEXESP; Sebastián-Gallés et al. 2000]. Visual complexity (VC) corresponds to ratings of the complexity of a drawing as defined by the number of lines in a drawing and their intricacy (Snodgrass and Vanderwart, 1980). Half of the pictures had high-VC (VC average 27973), and half low-VC (VC average 8581). The design therefore entailed 4 experimental conditions of 24 pictures each.

B. Experiment 2: Picture Naming Task II

This task was replicated from the study made by Strijkers et al. (2009). Sixty-four drawings of familiar objects from a wide range of semantic categories were selected. Two independent variables were manipulated: *Lexical Frequency* of the picture names and *Cognate Status* (Spanish - Catalan). Half of the pictures were classified as high-frequency words (lemma frequency average 52), and half as low-frequency words (lemma frequency average 3.9) [LEXESP; Sebastián-Gallés et al. 2000]. Half of the pictures were cognates, and half were not. Almost all cognates (27 out of 32) shared at least the whole first syllable with their corresponding translations, and all of them shared at least the first phoneme. The design therefore entailed 4 experimental conditions of 16 pictures each.

All images used in the study were black and white line drawings of familiar objects corresponding to Spanish words. Pictures were selected from the Snodgrass and Vanderwart (1980) set. In each task, participants had to overtly name every item which was presented once centrally and sequentially on the screen, in a pseudo-random order for 2000 ms followed by a fixation cross for 1000 ms (See figure 2).

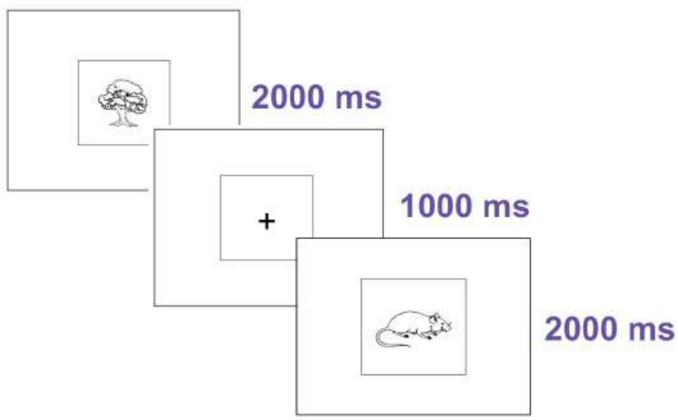

Figure 2. Example of stimuli used in Experiments 1 and 2.

Procedure.

Participants were evaluated individually in the IMIM-Hospital del Mar Epilepsy Unit, while they stayed for seizure monitoring. Given that seizure activity may induce cognitive effects that persist long after it is over (interictal activity), we ensured to test the participants at least two hours after a seizure (Vingerhoets, 2006; Hermann and Seidenberg, 2007). Participants were instructed to name the pictures that appeared on a computer screen as fast and accurate as they can in Spanish. The stimulus were presented with the software Processing 2.2.1 (Programming Software, 2001 https://processing.org/) on a laptop computer located approximately 60 cm away from the patient. Naming latencies (in milliseconds) were recorded by the same programme and the accuracy of the responses were scored manually by the experimenter. An electronic processor “Arduino; UNO” was used to connect and synchronize both hardware, the XLTEK system with the computer

(MacBook Pro). The application interfaced with an Arduino board that in turn was connected to the EEG amplifier, and at each trial a signal was sent through the Arduino to the EEG. The anatomical location of the electrodes and their approximate MNI coordinates were determined using 3D Slicer™ (Slicer 4.4.09) and SPM8 Matlab toolbox (Statistical Parametric Mapping software package, 2009 http://www.fil.ion.ucl.ac.uk/spm/software/spm8/) (for more details see 'Implantation Schemes' in Appendix 2 and 'Electrodes Location' in Appendix 3).

iEEG Data Acquisition.

Neurophysiological responses were registered by iEEG system from deep multichannel electrodes (DIXI Microtechniques, Besançon, France, 5–18 contacts; length, 2 mm, diameter, 0.8 mm; 1.5 mm apart) placed in both cortex and subcortical structures. The implantation scheme of each patient was bounded only for clinical reasons. The data were acquired continuously by the Neuroworks XLTEK system (version 6.3.0, build 636) at 32 kHz with a headbox of 128 channels recorded at a sampling frequency of 500 Hz per channel.

Behavioural Data.

Accuracy was obtained for all tasks. Response times were acquired for three of five participants due to technical problems with the software. Wrong answers (incorrect names), naming the picture in another language and disfluencies, were considered errors.

iEEG Data Processing and Analysis.

The electrophysiological data were analyzed for Evoked Event-Related Potentials (ERPs). Data were analyzed first in Matlab using the EEGLAB toolbox (Delorme and Makeig, 2004 http://sccn.ucsd.edu/eeglab/) and custom analysis and visualization routines. To remove any confounds from the common reference signal, a bipolar montage was constituted offline. Bipolar signals were derived by differentiating neighbouring electrode pairs of recorded and not rejected consecutive channels within the same electrode array. (Sahin et al., 2009; Burke et al., 2013; Dubarry et al., 2014). Post-processing steps included filtered the continuous EEG data through bandpass filter at 0.1-70 Hz and Notch (50 Hz), and segmented into 1200 ms epochs (starting 200 ms before stimulus presentation). Each epoch was labeled with its corresponding category and it was also identified as a failure or a hit depending on the patient's performance. Thereafter, the data were exported to BrainVision Analyzer 2.0.3 (© 2015 Brain Products. Munich, Germany) and normalized by baseline correction of -200 to 0 ms before stimulus onset. Epochs containing epileptiform spikes and/or artifacts were identified by visual inspection and, along with incorrect trials, were excluded from further time-domain analysis.

Malfunctioning electrodes that produced no usable data as well as electrodes located on the "seizure onset zone", were excluded from analysis. One patient (Patient C) was dismissed from the study because of a complex pattern of interictal activity in about 75% of experimental trials.

RESULTS.

It is important to consider that the results presented here are preliminary descriptive results and therefore any interpretation needs to be confirmed with further analysis or future experiments.

Since both tasks we used were similar, we found that they elicited a similar response pattern on each participant. The concerned pattern of activity was found in different brain areas that were predominantly posterior left sided, but also in the right hemisphere.

In Patient A, word-evoked triphasic activity appeared in Broca's area. The ~350 ms component was sensitive to word frequency. As can be seen in Figure 3, low frequency iERPs diverge from high frequency iERPs on its larger amplitude in the N350 component.

High vs. Low Frequency Condition iERP computed in Broca's area

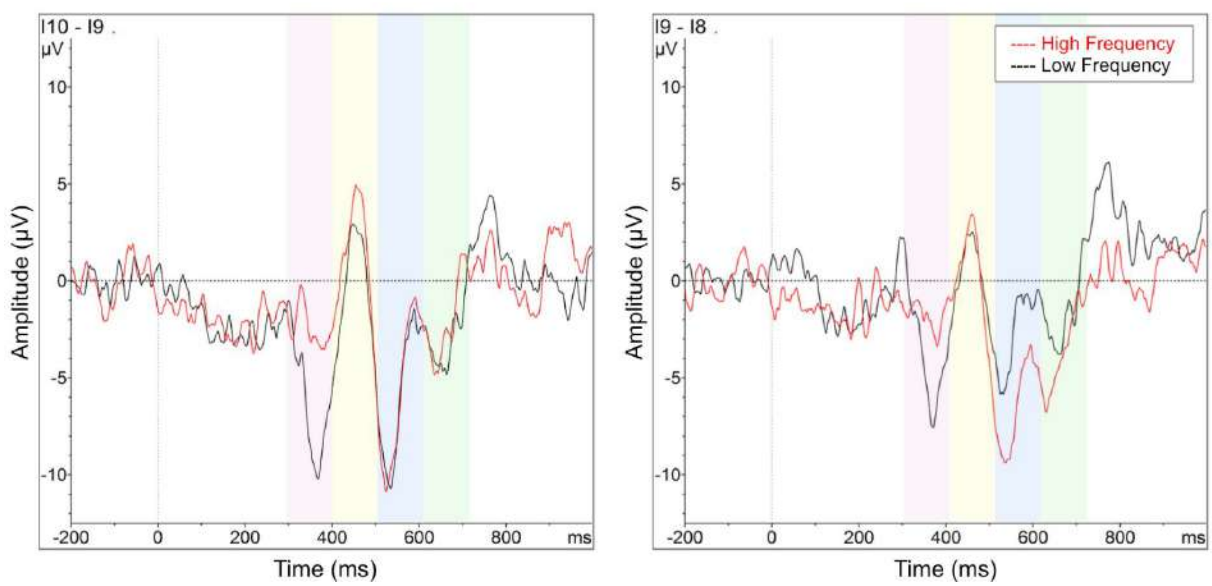

Figure 3. Broca's area triphasic waveform recorded from electrode I, in Patient A. iERPs computed from experiment 1. Red line signals the high-frequency word condition, black line signals the low-frequency word condition. A large difference in amplitude on the ~350 ms component between the two conditions is observed. The word frequency effect on that time window suggest that the lexical access phase was taking place.

We compared the pattern of iERP obtained with the results of the study by Sahin et al. (2009). In their results, iERPs in Broca's area displayed a three peaks sequence for lexical (~200 ms), grammatical (~320 ms), and phonological (~450 ms) processing. Even though our task was different, the potential we obtained had the same shape. Our iERP displayed a three peak sequence of great amplitude, but they emerged with a delay of 100 ms (Figure 4).

Confirmation of Broca's area triphasic activity

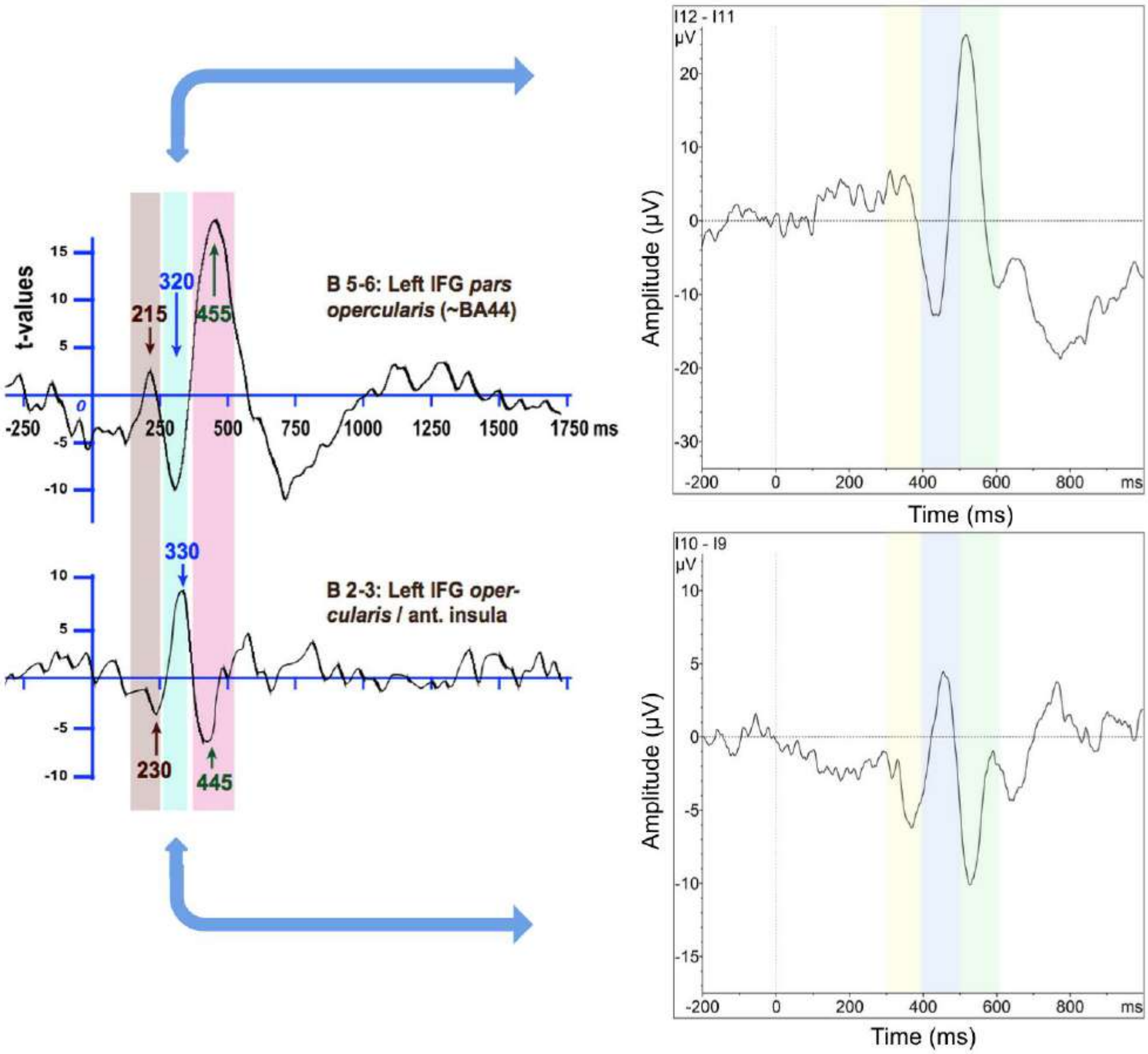

Figure 4. (Left) Figure taken from Sahin et al. (2009). Average all-condition iERP of a naming task. Neural activity recorded from a representative channel within Broca's area shows three local field potential (LFP) components that were consistently evoked by the task (~200, ~320, ~450 ms). The ~200 ms component is sensitive to word frequency, the ~320 ms LFP pattern suggests inflectional processing, and the ~450 ms component suggests phonological processing. Data were bandpassed between 1Hz and 20Hz. **(Right)** Replication of Broca's area triphasic activity in Patient A, electrode I, experiment 1. We used an arbitrary colormap to highlight the sequential phases of nomination that we have found computing the ERP. Notice that the scale changed. **(General)** The three consecutive waveforms suggest sequential linguistic processing. According to Sahin et al. (2009) each component might embody, respectively, lexical identification, grammatical inflection, and phonological processing in word production.

Other areas along the left temporal cortex, showed task related activity: the lateral temporal cortex generated iERPs characterized by a biphasic wave of great amplitude in both, ~300 ms and ~380 components. In left inferior temporal gyrus we found another triphasic waveform with peaks of increasing amplitude in timeframes corresponding to P4/N5/P6 respectively (see Figure 5 in 'Supporting Figures', Appendix 4). None showed to be sensitive to word frequency. Comparing the neural activity elicited by both task in the same patient and same electrode, we note that the iERPs were almost the same. This consistency across tasks is a proof of concept that the activity was not random (Figure 6). In some cases, neural activity recorded from several channels within the same electrode showed an inverted pattern of signal across neighboring virtual contacts (Figure 7).

In patients B, D & E, a biphasic waveform activity appeared bilaterally in the anterior occipital lobe, likely reflecting visual object recognition processing (see Figure 8 in 'Supporting Figures', Appendix 4). In our results, the negative and positive voltage deflections were localized in the latency range of ~320 to ~400 ms for the three patients.

Proof of concept: Consistency of neural activity across two tasks

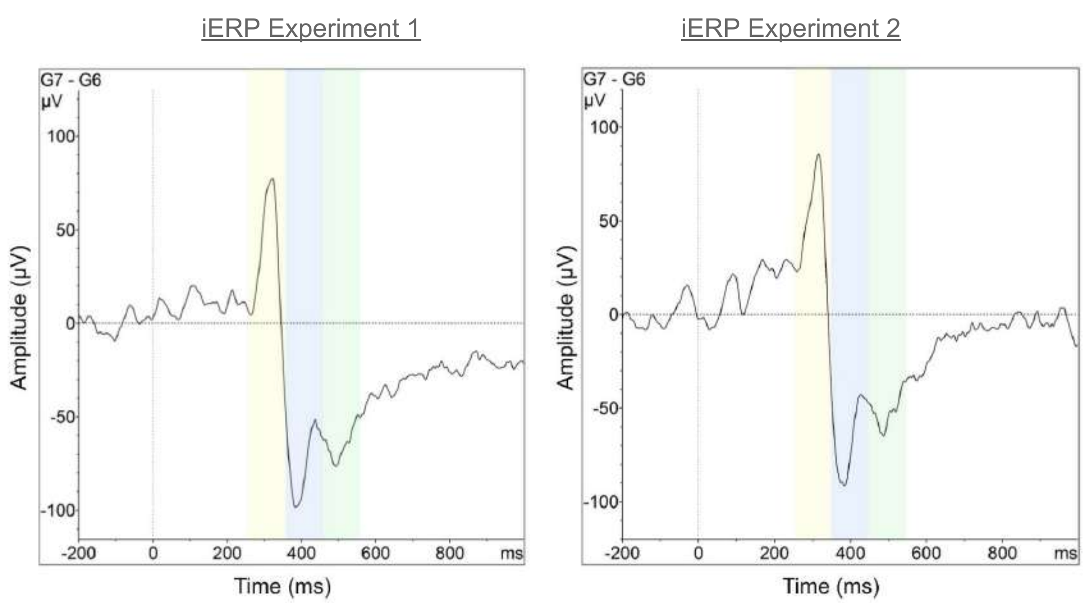

Figure 6. Consistency of task-related activity in Patient A, electrode G. Left figure corresponds to average all-condition iERP in experiment 1, and right figure shows average all-condition iERP in experiment 2.

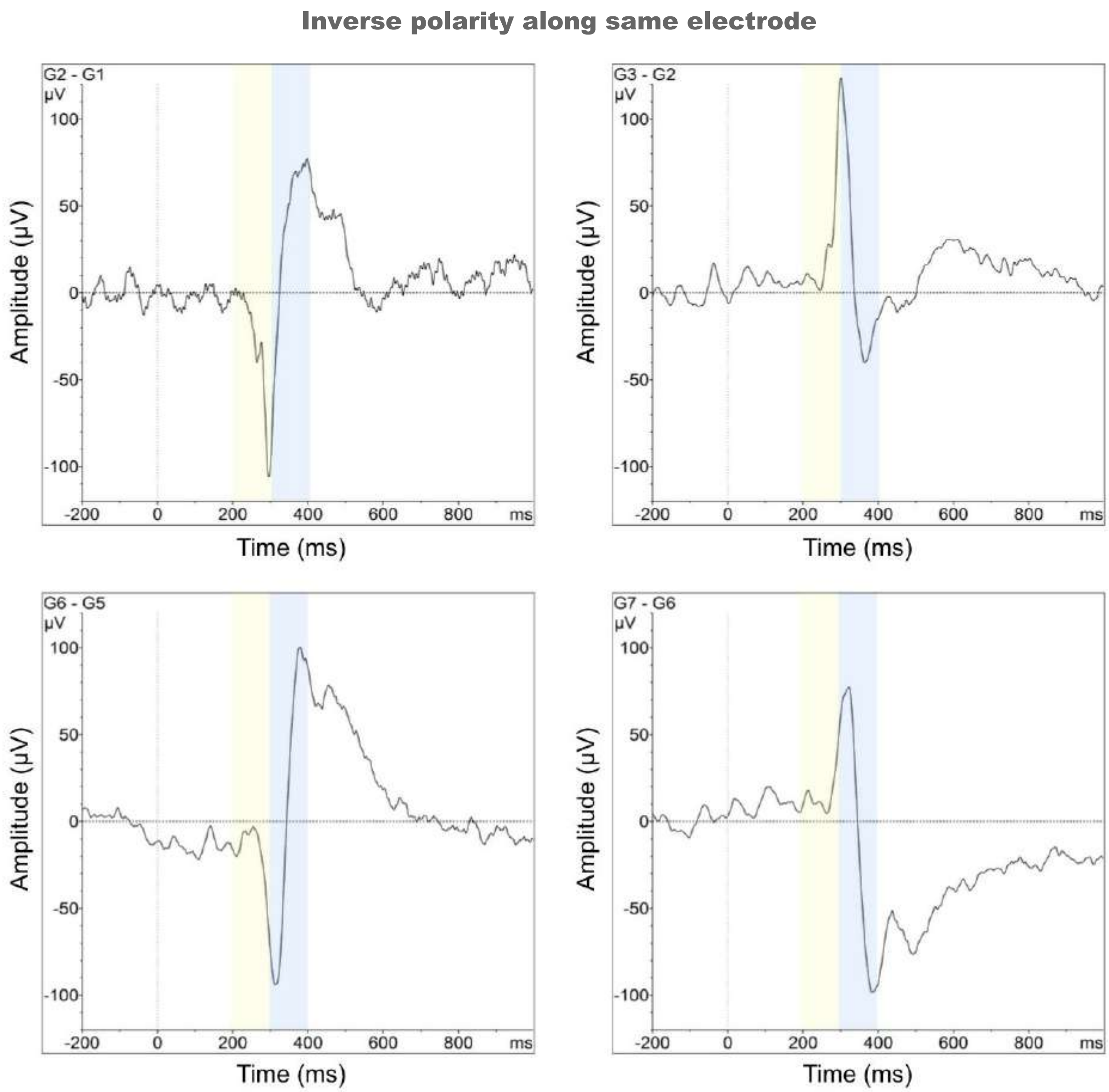

Figure 7. Patient A, Electrode G. Neural activity recorded from four bipolar differential channels along one electrode placed through the left temporo-parieto-occipital junction. iERPs computed from experiment 2 showed a biphasic wave with two clear components at ~300 and ~380 ms, respectively, that changed from positive to negative voltage deflections across neighboring channels. In all cases the peak differed from the baseline activity period.

DISCUSSION.

In the present study, we first aimed to implement an evaluation setting for cognitive research using a high-resolution spatiotemporal technique, intracranial electrophysiological recordings. We can ensure that the neuropsychological setup is correct and therefore it is possible to compute the data following the principles of intracranial Evoked Event-Related Potential (iERP) analysis.

Secondly, we investigated the spatiotemporal map associated with word production during overt picture naming. We used two similar tasks; they shared the same design and were divided in two conditions by word frequency. Because of this, both tasks had the same processing demands, and therefore consistent spatiotemporal activation patterns were observed across different brain areas on each participant. We found that word production activations began at ~300 ms after stimulus presentation and, as expected, we observed responses in Broca's area and the left temporal lobe.

One important finding of ours was the triphasic potential in Broca's area, which suggests that we could replicate the results published by Sahin et al. (2009). Early effects of lexical processing were found in the activation pattern. High frequency iERPs differed from low frequency iERPs at around ~350 ms after picture onset. The low frequency condition elicited larger amplitude in the N350 component, thus reflecting lexical access. We can ensure though, that lexical access was taking place in that time window but we can not demonstrate inflectional nor phonological processing, since we did not manipulate those conditions in our tasks. However, considering the spatiotemporal model of word production and the computational nature of the task, we can infer that the ~450 and ~520 components are consistent with the LFP patterns embodying grammatical inflection and phonological processing, respectively, in word production.

Another triphasic pattern was found in the left inferior temporal gyrus (ITG) starting at ~450 ms and followed by two peaks at ~520 and ~620 ms each. Through the ventral stream, the ITG is connected with the inferior occipital gyrus and the inferior surface of the temporal lobe. This pathway has been commonly associated with visual stimuli processing, visual object recognition (Gross et al., 1992) and mapping sound to meaning (Hickok and Poeppel, 2004). But also it might be related to word processing and lexical semantic recognition (Almairac et al., 1994; Nobre et al., 1994; Crone et al., 2001; Edwards et al., 2010; Acheson and Hagoort, 2013). Possibly, the later effects observed in the potential could be involved in auditory self-monitoring as the ventral stream also includes phonological level of representations for speech perception and immediate working memory (Hickok and Poeppel, 2007). Importantly, these results are not totally in line with the findings by Sahin et al. 2009, since they reported triphasic pattern activity confined exclusively to Broca's area.

To perform a naming a picture task, a series of hierarchical components are deployed from visual object recognition which provides an object concept. It is clear that visual object recognition processing is a necessary step during picture naming. This variable characterizes the time course of the visual processing implicated in the task. Early reliable effects can be seen in left posterior temporal–anterior occipital areas around ~150 ms (Miozzo et al., 2014) after the stimulus presentation. In our results, large negative LFPs with peak latencies near ~320 ms and ~400 ms were elicited bilaterally in posterior temporal–anterior occipital areas by both tasks. Our findings, in line with the ones reported by Tyler et al. (2004), suggest that picture naming recruits the two hemispheres to compute object recognition and word processing. However, electrodes were not implanted symmetrically so we can not contrast the activation of both hemispheres to draw more specific conclusions about what kind of information is being processed on each side.

When looking at neural activity recorded from several contacts within the same electrode, we found an inverted pattern of signal across neighboring virtual channels. This might indicate that the generators of the LFP components were local and that the peak inversions in time are due to different generators (Sahin et al., 2009). Meaning that different contacts were recording different stages of the process. Still, iERPs from the same neural phenomenon could have opposite polarity (Lachaux et al., 2012).

It is challenging to describe language processing through iEEG, since there are several limitations that must be considered when generalizing to healthy populations. Most constraints arise from the study population. An important issue is that the number of participants in this kind of study is small and limited to patients with chronic drug-resistant epilepsy. Furthermore, the site of implantation of the electrodes is determined solely on clinical grounds, makes it difficult to compare results across patients. Moreover, if we want to relate functional information to the time course of brain activation, it is essential to differentiate healthy brain tissue from the locations in the epileptogenic zone. Notably, it has been demonstrated that in epileptic patients, language is often reorganized and recruits more widespread processing networks with greater involvement of the non-dominant hemisphere (Powell et al., 2007). Even though when language produces the expected pattern of activation, the functional connectivity between language areas during rest is markedly different (Waites et al., 2006). Therefore, it is possible that the presence of a pathological epileptic network involved in seizure generation and propagation, disrupts the physiological language network involved in language generation and processing.

Since we have shown that our research setup is suitable for cognitive neuroscience research, future studies attempting to gather new knowledge about the neural circuits sustaining language processing can be carried out under this methodology. Future research can focus on what extent categorical information (e.g., semantic, grammatical) is driving the neural organization of word representation. Future experiments can gather new information regarding the orchestration of different brain circuits during language processing. More specifically, we can try to draw the neural spatiotemporal map (e.g., how different circuits sustaining different types of information are coordinated in time) associated with the production of speech. In conclusion, our results demonstrate that our assessment setting was experimentally viable and could potentially elucidate the neurophysiology of language processing.

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APPENDIX.

1. Patients and selection criteria.

Subject selection criteria. The study includes patients with drug-resistant epilepsy that, for diagnostic reasons, are implanted with microelectrodes that record brain activity in areas involved in speech production and contralateral ones. The placement of the electrodes is based solely on clinical criteria.

Subject inclusion criteria. The study includes adults of both sexes, indistinct laterality, aged between 18 and 65 years, diagnosed with focal epilepsy resistant to drug treatment, without intellectual disability (IQ> 70) and attending the Epilepsy Unit of Hospital del Mar to be implanted with intracerebral electrodes.

Subject exclusion criteria. This study excludes patients who had at least one of the conditions presented below: Intellectual disability (IQ <70); illiteracy; moderate or severe visual deficits which are uncorrectable with the use of glasses or contact lenses; major depression; psychotic disorder and/or anyone who refuses to participate in the study.

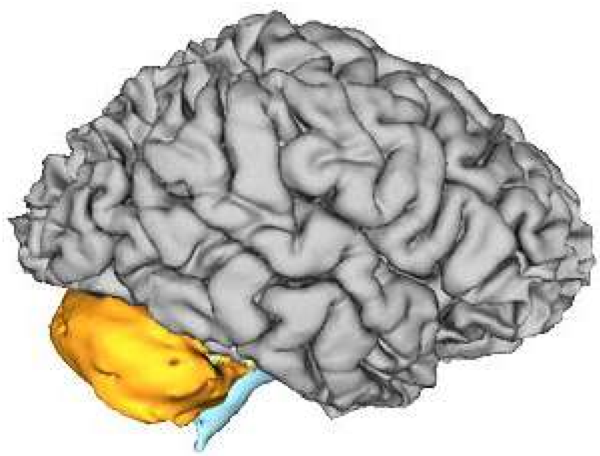
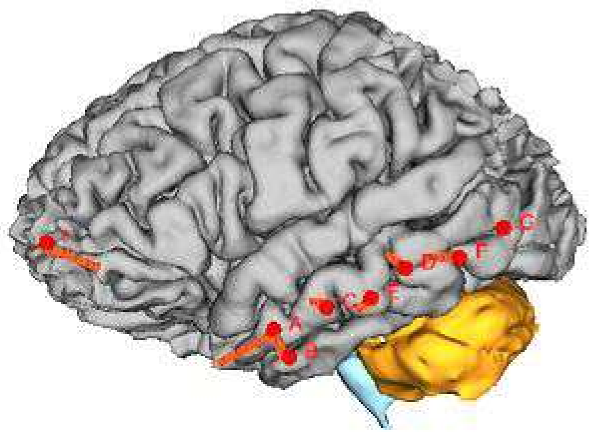
Subject withdrawal criteria. Subjects who presents at least one condition of the ones presented below, are excluded from the study: Complications of the implantation, complications of their health status (status epilepticus, stroke, infections, etc); location of epileptogenic focus in areas that interferes with the neurophysiological recording and/or voluntary decision to cease participation.

Patient	Sex	Age	Seizure Onset Age	Handedness*	Years of education	IQ (WAIS-III)	Dx. NPS
A	Male	38	2	Right-handed	16	105	Mild dysexecutive disorder
B	Male	44	Early childhood	Right-handed	10	106	Mild dysexecutive disorder
C	Female	34	12	Right-handed	17	105	Verbal memory déficit & anomia
D	Female	45	40	Right-handed	8	105	Verbal memory déficit
E	Male	44	19	Right-handed	12	135	Verbal memory déficit

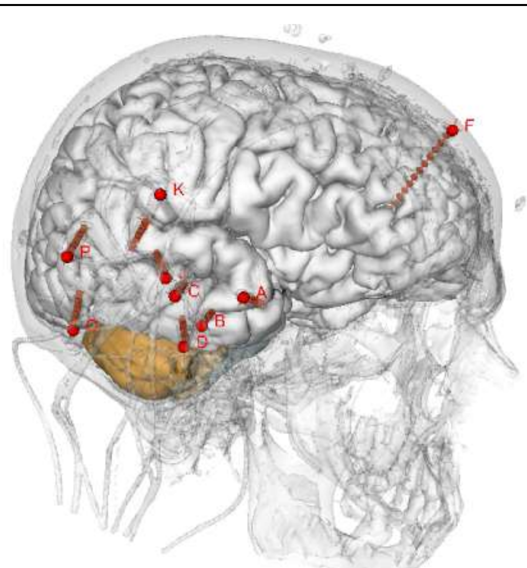
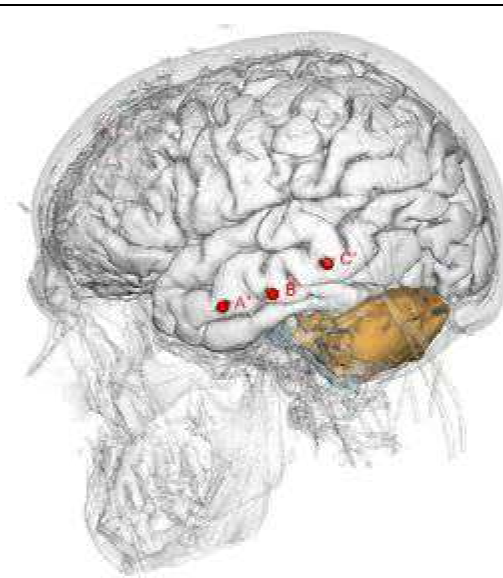
Table 1. Patient information. Patient B did not refer the exact seizure onset age, but reported febrile seizures onset at 9 months of age. *Handedness in all control participants was assessed with the Edinburgh Handedness Inventory (Oldfield, 1971). (IQ: Intelligence quotient)

2. Implantation schemes.

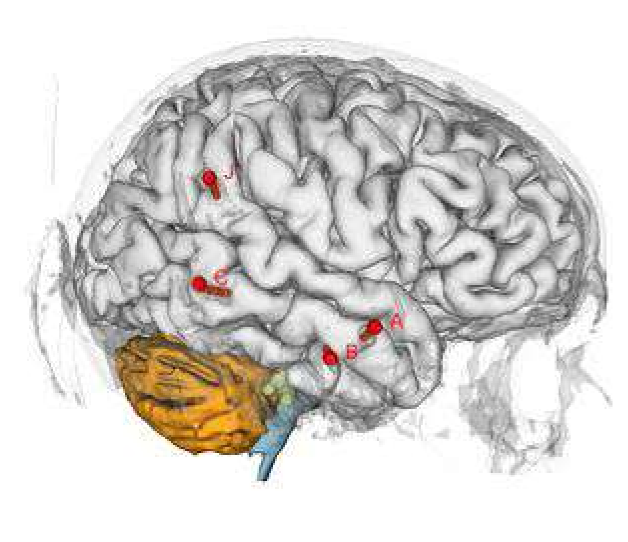
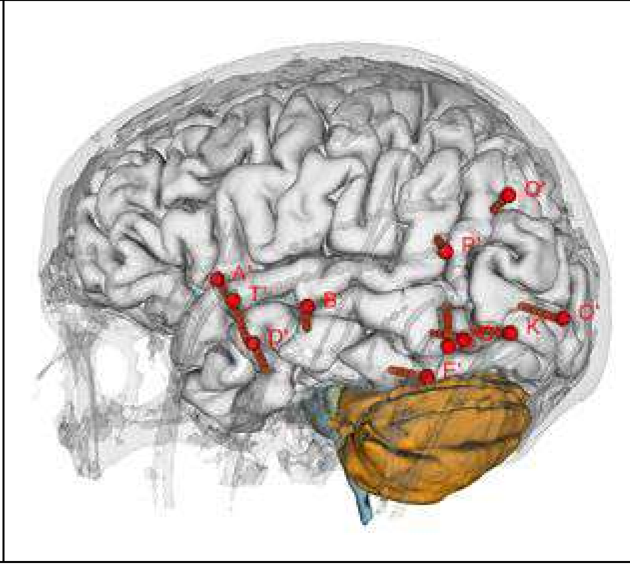
Patient A. Nine electrodes were implanted in the left hemisphere. 85 channels recorded brain activity continuously.

Right Hemisphere	Left Hemisphere
	

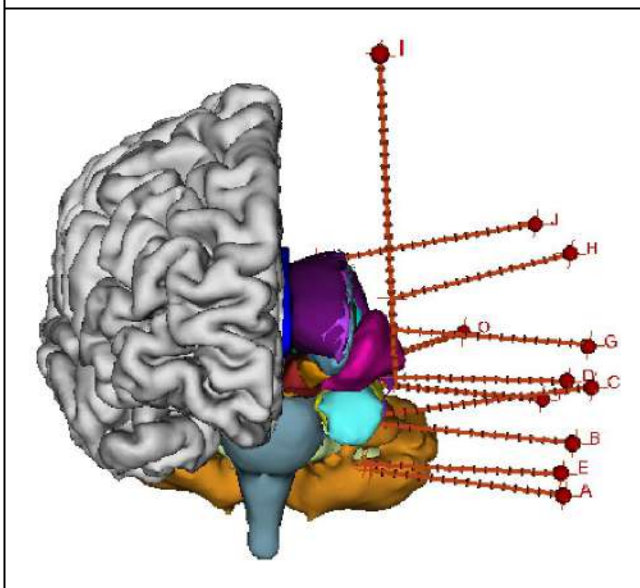
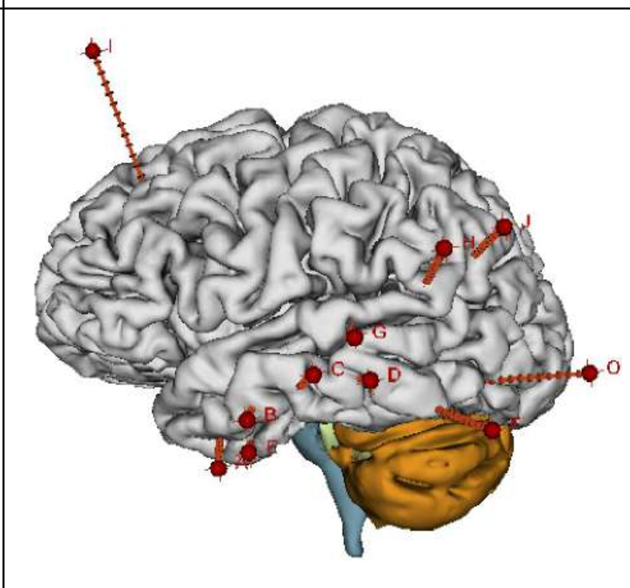
Patient B. Three electrodes were implanted in the left hemisphere, and nine on the right. 124 channels recorded brain activity continuously.

Right Hemisphere	Left Hemisphere
	

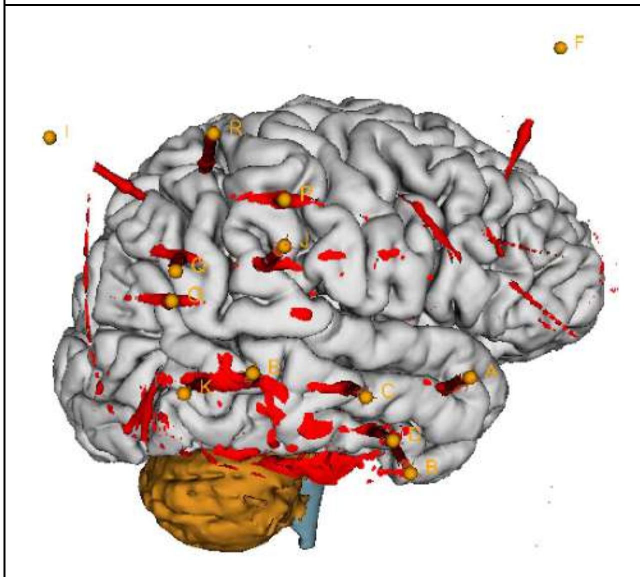
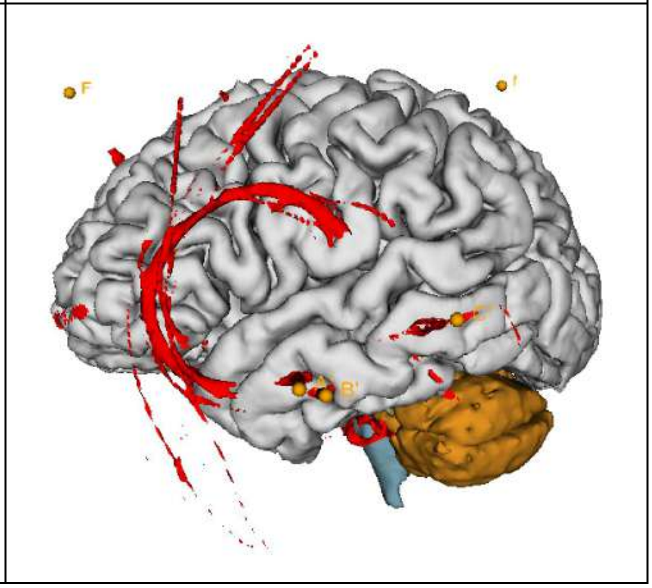
Patient C. Eleven electrodes were implanted in the left hemisphere, and four on the right. 125 channels recorded brain activity continuously.

Right Hemisphere	Left Hemisphere
	

Patient D. Eleven electrodes were implanted in the left hemisphere. 125 channels recorded brain activity continuously.

Right Hemisphere	Left Hemisphere
	

Patient E. Three electrodes were implanted in the left hemisphere, thirteen on the right. 125 channels recorded brain activity continuously.

Right Hemisphere	Left Hemisphere
	

*All images were created using the 3D Slicer™ (Slicer 4.4.0 r23774 Released. Multi-platform software package for visualization and medical image computing http://www.slicer.org/).

3. Electrodes location.

By mixing presurgical and post-implantation brain computerized tomography (TC) with the magnetic resonance image (MRI), a 3D template was created. We matched it to standard brains from the Montreal Neurological Institute using SPM8 and to obtain MNI coordinates for each contact.

Patient A.

Electrode Contact	X Coordinate (left to right)	Y Coordinate (posterior to anterior)	Z Coordinate (ventral to dorsal)
E3	-46.3	-5	-37.4
E4	-49.5	-4.9	-36.6
G1	-20.3	-55.5	-24.8

G2	-23.9	-54.8	-24.3
G3	-27.4	-54.2	-23.7
G5	-34.6	-52.8	-22.7
G6	-38.2	-52.1	-22.2
G7	-41.7	-51.5	-21.6
I8	-33.5	54.9	-10.1
I9	-36.6	56.3	-8.5
I10	-39.7	57.7	-6.9
I11	-42.7	59.1	-5.3
I12	-45.8	60.5	-3.7

Patient B.

Electrode Contact	X Coordinate (left to right)	Y Coordinate (posterior to anterior)	Z Coordinate (ventral to dorsal)
O4	42.9	-76	-1
O5	46.6	-75.3	-2.1

4. Supporting figures.

Left inferior temporal cortex triphasic activity

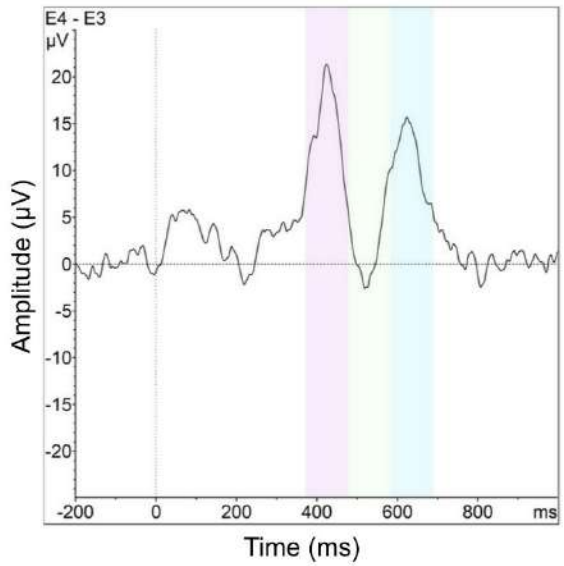


Figure 5. All conditions iERP computed from experiment 2 in Patient A, electrode E. Three LFP components evoked at ~420, ~520 and ~620 ms each.

Posterior temporal-anterior occipital iERPs

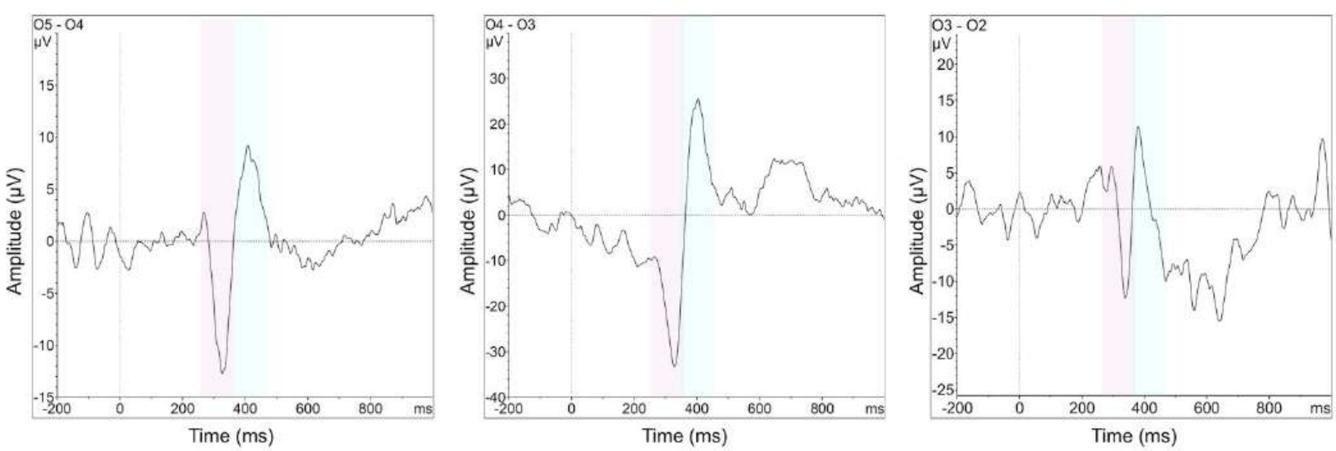


Figure 8. iERPs reflecting biphasic waveform activity in posterior temporal–anterior occipital areas during experiment 1. **(Left)** Patient B, electrode O in right hemisphere. **(Middle)** Patient D, electrode O in left hemisphere **(Right)** Patient E, electrode O in right hemisphere *Note that the amplitude scale changed.