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Activity Associated with Speech Articulation Measured Through Direct Cortical Recordings

Alexandra Basilakos, Ph.D.[1], **Julius Fridriksson, Ph.D.**[1], **Chris Rorden, Ph.D.**[2], **Roozbeh Behroozmand, Ph.D.**[1], **Taylor Hanayik**[2], **Thomas Naselaris, Ph.D.**[3], **John Del Gaizo**[3], **Jesse Breedlove**[3], **W.A. Vandergrift III, M.D.**[4], and **Leonardo Bonilha, M.D., Ph.D.**[3]

[1]Department of Communication Sciences and Disorders, University of South Carolina, Columbia, SC, 29208

[2]Department of Psychology, University of South Carolina, Columbia, SC, 29208

[3]Department of Neurology, Medical University of South Carolina, Charleston, SC, 29425

[4]Department of Neurosurgery, Medical University of South Carolina, Charleston, SC, 29425

Abstract

The insula has been credited with a role in a number of functions, including speech production. Here, we recorded electrocorticography (ECoG) signals from the left insula during pseudoword articulation in two patients undergoing pre-surgical monitoring for the management of medically-intractable epilepsy. Event-related band power (ERBP) activity from electrodes implanted in the superior precentral gyrus of the insula (SPGI) was compared to that of other left hemisphere regions implicated in speech production. Results showed that SPGI contacts demonstrated significantly greater ERBP within the high-gamma frequency range (75–150 Hz) during articulation compared to a listening condition. However, frontal and post-central regions demonstrated significantly greater responses to the articulation task compared to the SPGI. Results suggest the SPGI is active during articulation, but frontal and post-central regions demonstrate significantly more robust responses. Given the small sample size, and number of electrodes implanted in the SPGI, further study is warranted to confirm these findings.

Keywords

Articulation; Electrocorticography; Insula; Speech production

Corresponding Author: Leonardo Bonilha, M.D., Ph.D., Department of Neurology, Medical University of South Carolina, 96 Jonathan Lucas St., Charleston, SC, Zip: 29425.

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1. Introduction

The insular cortex has been credited with a number of roles, ranging from communication (e.g., Ackermann & Riecker, 2004; Ackermann & Riecker, 2010; Ardila, 1999; Ardila, Benson, & Flynn, 1997; Baldo, Wilkins, Ogar, Willock, & Dronkers, 2011; Dronkers, 1996; Dronkers, Ogar, Willock, & Wilkins, 2004; Nagao, Takeda, Komori, Isozaki, & Hirai, 1999; Ogar et al., 2006), visceral functions (e.g., Augustine, 1985; Craig, 2002, 2009; Mayer, Naliboff, & Craig, 2006; Moisset et al., 2010), conscious awareness (Craig, 2009), addiction (Naqvi & Bechara, 2009, 2010), and psychiatric disorders (Klein, Ullsperger, & Danielmeier, 2013). The participation of the insula in visceral, emotional, and conscious processes is supported by theoretical models (e.g., Craig, 2002, 2009). However, the relationship between insular function and communication is less rooted in models of language production (e.g., Hickok, 2014; Tourville & Guenther, 2011), even though several studies have reported that the insula is implicated in communication disorders, such as apraxia of speech (AOS; a disorder of motor speech planning and programming that results in off-target articulation, speech sound distortions, and prosodic abnormalities) and aphasia.

To date, lesion-deficit studies of individuals with AOS have informed the study of the neuroanatomical correlates of speech production processes (e.g., Baldo et al., 2011; Basilakos, Rorden, Bonilha, Moser, & Fridriksson, 2015; Dronkers, 1996; Dronkers & Ogar, 2004; Dronkers et al., 2004; Graff-Radford et al., 2014; Hickok et al., 2014; Hillis et al., 2004; Itabashi et al., 2016; Richardson, Fillmore, Rorden, Lapointe, & Fridriksson, 2012). The earliest systematic, quantitative study that revealed a role of the insula in speech was conducted by Dronkers (1996). That study showed 100% lesion overlap in the superior precentral gyrus of the insula (SPGI) in patients with AOS, but 0% lesion overlap in the SPGI among patients without AOS. The relationship between the insula and speech was subsequently supported by functional imaging (Moser et al., 2009; Wise, Greene, Büchel, & Scott, 1999) and lesion (Nagao et al., 1999; Dronkers et al., 2004; Ogar et al., 2006) studies.

The insula as the primary region implicated in AOS has not been a unanimous finding. In a sample of acutely post-stroke patients, Hillis et al. (2004) found that insula damage was not a prerequisite for AOS. Instead, in their sample of patients with AOS (n=31) over half (n=19) did not demonstrate hypoperfusion to the insula; rather, hypoperfusion to the left inferior frontal gyrus *pars opercularis* (IFGpo) was more likely (n=26/31 patients). These findings were confirmed by an independent group of individuals at the chronic stage of stroke (≥6 months post-onset; Richardson et al., 2012). However, more recent studies suggest a role of the frontal motor and post-central areas in AOS. Collectively, these studies have suggested that pre- and post-central regions may instead be the areas crucially involved in planning, monitoring and executing the motor aspects of speech (Basilakos et al., 2015; Graff-Radford et al., 2014; Hickok et al., 2014; Hillis et al., 2004; Josephs & Duffy, 2008; Josephs et al., 2012; Whitwell et al., 2013).

1.2 Results from Intracranial EEG Studies

With its high temporal and anatomical resolution, electrocorticography (ECoG) has the advantage of providing rare data from brain activity within multiple target regions. Although several prior studies have used ECoG to investigate the role of auditory and motor cortices

during speech production (e.g., Behroozmand et al., 2016; Chang, Niziolek, Knight, Nagarajan, & Houde, 2013; Greenlee et al., 2013; Kingyon et al., 2015), relatively fewer studies have investigated regions that are involved during overt production (e.g., see Bouchard, Mesgarani, Johnson, & Chang, 2013; Flinker et al., 2015).

Until relatively recently, direct cortical recordings from the insula were less feasible due to the insula's anatomical intricacies, being concealed from the lateral surface of the brain by the frontal and temporal opercula and covered by multiple branches of the middle cerebral artery. Advanced improvements in stereotaxic surgical techniques have resulted in successful ECoG electrode implantation in the insula (Isnard, Guénot, Sindou, & Mauguière, 2004) through stereoEEG (sEEG). To our knowledge, no published studies thus far have provided accounts of direct cortical recordings from the insula, or the SPGI specifically, during speech production.

Here, we report ECoG recordings from the SPGI in two patients without visible structural brain lesions who were undergoing pre-surgical monitoring of medically intractable epilepsy. The purpose of this study was to measure the SPGI's response to speech production, compared to other grey matter regions of interest previously implicated in speech production based on the results of lesion studies (e.g., Dronkers, 1996; Baldo et al., 2011; Graff-Radford et al., 2014; Basilakos et al., 2015) and fMRI studies in non-brain damaged individuals (e.g., Wise et al., 1999) (see regions listed in Table 1). To this end, we aimed to test: 1) whether the SPGI would demonstrate greater response during articulation when compared to a non-articulation task, and 2) the relative magnitude and timing of cortical responses from the SPGI compared to other left hemisphere frontal and post-central regions during articulation.

2. Method

2.1 Participants

Two patients with surgically implanted electrodes undergoing monitoring for intractable epilepsy were recruited for study. Both patients were female, right-handed, ages 33 (Patient 1) and 31 (Patient 2). Epilepsy onset was six years prior to testing for Patient 1, and 14 months for Patient 2. Neither patient reported premorbid speech and/or language difficulties or concomitant neurological impairment in addition to epilepsy. Clinical pre-surgical neuroimaging was unremarkable for any structural brain abnormalities. During pre-surgical evaluation of their epilepsies, both patients had poorly localized and poorly lateralized seizure onsets during ictal scalp EEG monitoring, leading to broad bilateral sEEG coverage to further elucidate seizure onset. Results from sEEG monitoring revealed that both patients had seizures localized to medial temporal lobes (MTL): Patient 1 had independent seizure onset on the right and left hippocampi, whereas Patient 2 had right hippocampal seizure onset. The insula was neither the location of ictal onset nor was it involved in seizure propagation in either one of the patients. None of the recorded seizures was poorly localized.

A WADA test was not indicated for Patient 1 since resective surgery was not possible and the patient subsequently underwent treatment with responsive neurostimulation implanted on the MTL bilaterally. Since Patient 1 was right handed and the recordings from the left

frontal electrodes indicated neuronal activity related to speech articulation (as described below), the left hemisphere was considered dominant for language. Patient 2's WADA testing revealed language processes were lateralized to the left hemisphere.

Patients consented to testing by signing an informed consent form approved by the Institutional Review Board at the Medical University of South Carolina.

2.2 ECoG Contacts and Localization

Patients were surgically implanted with 10-channel sEEG depth electrodes (0.86 mm diameter, 5 mm spacing; Ad-Tech Corporation, Racine, WI) prior to testing. Exact electrode coordinates were determined using post-implant structural T1-MRI Coordinates for each electrode were obtained through the following procedures. First, using MRIcron software, electrodes were "masked" on each patient's native T1-MRI This was completed for all contacts for each patient. Electrode masks were then used in the estimation of normalization parameters using the cost-function masking (Brett, Leff, Rorden, & Ashburner, 2001) features in the Clinical Toolbox (Rorden, Bonilha, Fridriksson, Bender, & Karnath, 2012) for SPM8 to ensure that tissue surrounding electrode locations would be normalized without interference from the electrode sites The normalized, skull-stripped T1 images were visually inspected for distortions and then used to identify specific coordinate locations for each individual channel in standard space. The central point of each sEEG electrode was manually localized and anatomical coordinates were recorded and compared with spatial coordinates from the Automated Anatomical Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002) and with the previous literature on the SPGI anatomical boundaries (Dronkers, 1996; Fedorenko, Fillmore, Smith, Bonilha, & Fridriksson, 2015). We selected channels of interest from the insular, frontal, and post-central cortices across the left hemisphere. For both patients, a measure of insular activity during speech production was recorded from the SPGI, in addition to a measure of posterior insula activity recorded from Patient 2. Prefrontal recordings were taken from superior frontal gyrus (SFG; Patients 1 and 2), the middle frontal gyrus (Patient 2) and the inferior frontal gyrus *pars triangularis* (IFGpt; Patient 1). Last, an electrode located in the post-central gyrus (PoCG; Patient 1) served as a measure of post-central cortical activity. Note that electrode locations differed slightly between the two patients due to individualized variations of sEEG electrode placement given cortical anatomy and pre-surgical planning. The anatomical coordinates of each chosen contact are presented in Table 1, and will be referred to by lobar region throughout the remaining text. Figure 2 displays T1 scans for each patient, with crosshairs at each channel of interest. Since sEEG depths are placed orthogonally to the pial surface, some electrodes are situated in the cortex, while other are in the cortical pial transition, gray and white matter transition, or in the white matter. In order to accurately sample from cortical sources, for each depth, we chose the electrodes whose placement was in the center of the cortical depth and not in the cortical inner or outer boundary zones.

2.3 Design, Materials, and Procedure

The articulation task consisted of listening and repeating twelve different bisyllabic pseudowords presented over eight blocks (96 total trials). Pseudowords were chosen instead of real words to emphasize that the ECoG measurements reflected articulation as opposed to

lexical processing. The pseudowords were recorded by a native English speaker in a neutral accent. The second syllable of each stimulus was always a consonant vowel (CV) syllable (e.g., __fo, __po), and the first syllable of each pseudoword was either a simple CV structure (e.g., pow__, bih__) or consonant cluster, compatible with the English language (e.g., tr__, fr__). Pseudowords were adapted from Fedorenko et al. (2015).

The PsychToolbox (Brainard, 1997) for Matlab (version 2012a, Mathwoks, Natic MA), was used for the presentation of the pseudowords and to record each patient's responses. In each trial, a pseudoword was auditorily presented. Each contact's response to this auditory presentation was recorded, herein referred to as the *Listen* condition. Following a 3000 ms delay, a visual cue appeared on the computer screen, and patients were instructed to repeat the pseudoword as soon as this cue appeared. 3000 ms were allowed for speech production. ECoG signal response during pseudoword production is herein referred to as the *Speech* condition. To avoid patient fatigue, total experimental testing did not exceed 15 minutes. Patient responses were audio recorded for the purpose of offline scoring.

2.4 Data Acquisition and Analysis

ECoG data were recorded using a XLTEK EEG system (Natus Medical, Inc.) at a sampling rate of 2 KHz. Each speech stimulus prompt and the visual cues for patient pseudoword production were marked separately in the EEG signal using a photodiode pulse synched to the onset and offset of each event. These pulses were used to identify the occurrence of experimental events in the recorded ECoG signals. Patients' speech responses were recorded using the same experimental computer using Matlab and Psychtoolbox at 44.1 KHz.

ECoG data were converted using EEGLab and imported to Matlab for preprocessing and analysis using in-house developed Matlab scripts. The data were first band pass filtered at 1–300 Hz, and a notch filter was applied for the 58–63 Hz band. Channels with excess noise were identified and removed through the following process: the mean activity of all channels was calculated and we removed channels that demonstrated mean activity greater than one standard deviation higher or lower than the grand mean of all channels. The mean activity of the remaining channels was then used as an average reference for further analysis. Data were baseline corrected by subtracting the mean activity compared with the time window encompassing 1000 ms before the onset of the presented stimulus (*listen* condition) or the cued speech onset (*speech* condition).

Time–frequency analysis of the ECoG signals was performed on a trial-by-trial basis using a complex Morlet wavelet transform (Oya, Kawasaki, Howard, & Adolphs, 2002) with center frequencies ranging from 1 to 300 Hz with 1 Hz spectral resolution. The wavelet constant ratio was defined as $f_c/\sigma_f = 10$, where f_c is the center frequency of the wavelet and σ_f is its standard deviation in frequency domain defined as $\sigma_f = 1/(2\pi\sigma_t)$. At 100 Hz, this leads to a wavelet width ($2\sigma_t$) of 31.8 ms and to a spectral bandwidth ($2\sigma_f$) of 20 Hz. The wavelet convoluted ECoG data corresponding to the auditory presentation of each pseudoword (*Listen* condition) and patient response (*Speech* condition) were calculated for each condition as an event-related band power (ERBP) response for each electrode according to the following formula:

$$\mathrm{ERBP}\,[dB] = 10 \times \log 10 \left(\frac{P}{P_{\mathrm{Baseline}}} \right)$$

The log transformation function was used to ensure that the data were normally distributed for statistical analysis. ERBP responses for the pseudoword presentation (*Listen* condition) were calculated by normalizing signal power P following presentation of the pseudoword stimulus, relative to the power at baseline ($P_{basline}$; 1000 ms duration prior pseudoword presentation). ERBP for speech responses was computed similarly, with signal power P normalized following each patient's production, relative to 1000 ms prior to the visual cue for speech onset.

ERBP for trials in each condition (*Listen* and *Speech*) were then averaged for each electrode location into 100 ms time bins from 500 ms prior to the cued response interval, and allowing 3000 ms for speech response. This resulted in 30 bins for further analysis (note that the last bin from each analysis was removed due to edge artifact). Finally, mean ERBP responses for each channel across the *Listen* and *Speech* conditions were compared with two separate 2×4 (*condition × channel*) within-subjects repeated measures ANOVAs (using SPSS, version 24). ANOVA results were followed-up with post-hoc pairwise comparisons for each channel's mean ERBP response. All comparisons were Bonferroni corrected for multiple comparisons for channel (i.e., p=0.05 divided by six channel comparisons, yielding a significant p-value of p<0.008). Since mean ERBP responses were collapsed per channel across time, we did not correct the p value based on the number of time bins.

3. Results

3.1 Behavioral performance

Both patients completed the articulation task with high accuracy (Patient 1: 90%; Patient 2: 92%), with the infrequent errors consisting of sound substitutions, omissions, distortions and additions. Mean latency to speech onset was 827.11 ms (SD=302) for Patient 1 and 553.15 ms (SD=189.7) for Patient 2.

3.2 Mean ERBP responses by condition

All channels demonstrated significantly greater high-gamma (75–150 Hz) ERBP during *Speech* versus *Listen*. There were significant condition by channel interactions for both patients: Patient 1: $F(3, 87)=28.99$,p<0.001, partial η^2=0.50; Patient 2: $F(3, 87)=124.96$, p<0.001, partial η^2=.81. We did not observe significant increase in ERBP during *Speech v. Listen* for other frequencies (alpha: 8.5–13Hz, beta: 13.5 – 30Hz, low gamma: 30–75Hz). Accordingly, ERBP in the sections that follow refer to responses in the high gamma range.

3.3 Channel comparisons

Overall, ERBP was greater for the *Speech* conditions compared to the *Listen* conditions (mean difference between conditions for Patient 1: 0.51, p<0.0001; Patient 2: 0.76, p<0.0001). Mean ERBP for all channels for both conditions in presented in Figure 2.

Bonferroni corrected pairwise comparisons for each channel of interest for each condition are as follows:

Inspection of ERBP responses for Patient 1 during the *Listen* condition revealed no significant differences in ERBP for the two frontal channels (p=0.014) or between the Insular and Frontal 1 channel ($p=0.029$). The Post-central channel had the greatest ERBP compared to all other channels (p<0.005 for all). The Frontal 1 channel had the smallest ERBP response, significantly different from the Insular [t(29)=4.93, p<0.001] and Post-central channels [t(29)=9.53, p<0.001]. For Patient 2, all channels were significantly different during *Listen* (Bonferroni corrected-p<0.008), except for the two frontal channels (p=0.009). Both insula channels (i.e., SPGI, posterior insula) demonstrated significantly greater ERBP than the frontal channels [(Insular 1 v. Frontal 1: t(29)=4.1, p<0.001; Insular 1 v. Frontal 2: t(29)=8.61, p<0.001); Insular 2 v. Frontal 2: t(29)=10.321, p<0.001; Insular 2 v. Frontal 1: t(29)=6.94, p<0.001], and Insular 2 channel was significantly greater than Insular 1 [t(29)=3.109, p<0.005].

During the *Speech* conditions, mean ERBP responses for Patient 1 showed that the Insular 1 channel (i.e., the SPGI) had the lowest mean ERBP when compared to both the frontal and the post-central channels (p<0.001 for all comparisons). For Patient 2, the Insular 1 and Frontal 1 channels did not differ in ERBP response (p=0.009), but all other channels differed significantly (p<0.001 for all). Inspection of channels with the greatest mean ERBP during the *Speech* conditions shows that for Patient 1, mean ERBP of the post-central region was significantly greater than that of all other regions (Post-central v. Frontal 1: t(29)=7.98, p<0.001; Post-central v. Frontal 2: t(29)=8.04, p<0.001; Post-central v. Insular: t(29)=14.84, p<0.001). For Patient 2, mean ERBP of the Frontal 2 channel was significantly greater than all other channels (Frontal 1 v. Frontal 2: t(29)=7.89, p<0.001; Frontal 1 v. Insular 1: t(29)=10.3, p<0.001; Frontal 1 v. Insular 2: t(29)=11.56, p<0.001).

We subsequently investigated the time point in which ERBP for *Speech* conditions differed significantly from the *Listen* conditions. For Patient 1, the Post-central channel was the first region to demonstrate a significantly higher ERBP in *Speech* when compared to *Listen* (at the 100 ms time bin), followed by Frontal 2 (800 ms time bin), Insular (1000 ms) and Frontal 1 (1200 ms). For Patient 2, differences emerged in all four channels at the 100 ms time bin following the cue to speak. Figure 3 (panels A and B) presents mean ERBP for each 100 ms time bin for the *Speech* conditions. The first time bin in which ERBP in the *Speech* condition significantly exceeded the *Listening* condition are marked with an asterisk.

4. Discussion

Using ECoG recordings, the present study demonstrated a direct increase in high gamma ERBP activity in left hemisphere frontal and post-central regions during pseudoword articulation. In contrast, the insular cortex had a tendency toward eliciting significantly weaker high gamma activity compared with the frontal and post-central cortex during pseudoword articulation. This pattern was seen across both patients. Although there were slight differences in activity between the frontal channels for both mean high-gamma response and the ERBP response over time, it should be noted that the exact placement of

the electrodes differed between patients, and therefore, ERBP activity in the selected channels is a broad representation of frontal lobe regions during speech production.

As is the case with most ECoG studies collecting invasive and valuable data, our results are limited by the small number of patients and by the fact that both patients suffered from uncontrolled epilepsy. Even though there were no visible structural lesions on the location of the electrodes, it is not possible to ascertain that the underlying cortex is similar to the general population. Nonetheless, both patients were able to complete the task with few errors[1], and the studied electrodes were not placed at the location of seizure onset. Specifically, the seizure onsets were restricted to the MTL - bilateral independent MTL for Patient 1 and restricted to the right MTL for Patient 2. The insula was not implicated in seizure onset or in seizure propagation in both cases. None of the recorded seizures were poorly localized or succeeded clinical seizure manifestations. Although the MTL is implicated in some aspects of lexical production (e.g., semantic processes; Visser, Jefferies, Embleton, & Lambon Ralph, 2012), it is not implicated in motor speech production or articulation. Accordingly, we contend that seizure onset locus was unlikely to have influenced recording sites or performance for this task. Since direct cortical recordings from the insula are exceptional and no previous studies have reported SPGI recordings during an articulation task, we believe that this study provides unprecedented insights into the magnitude and timing of evoked cortical responses during speech production.

Based on these results, we suggest that the insula's role in motor speech production is secondary to the activity in the pre- and post-central areas, but further study is warranted to confirm these findings. Here we found that the insula is active during articulation, but that it may not play a primary role in production (see also Fedorenko et al., 2015). From our sample, the earliest peak gamma activation was noted in the post-central region, which is in accordance with contemporary models of motor speech control such as the Hierarchical State Feedback Control (HSFC) model (Hickok, 2012; Houde & Nagarajan, 2011) and the Directions into the Velocities of Articulators (DIVA) (Guenther & Vladusich, 2012; Tourville & Guenther, 2011). According to these models, speech motor control depends on the sensorimotor transformation of stored auditory targets, accessed via post-central regions, into articulatory targets, which are planned and executed in frontal motor regions (Hickok, 2012). Although it has been argued that pseudoword stimuli "isolate" articulatory processes (e.g., Hickok & Poeppel, 2004), a caveat is that the computations required for pseudoword articulation may place greater processing demands upon the auditory-motor system (e.g., Baldo et al., 2012; Rogalsky et al., 2015). That is, results from two lesion-symptom mapping studies where post-stroke individuals completed pseudoword repetition tasks showed that the extent of lesion damage related to pseudoword repetition was spatially similar to that of real word repetition, but spatial representation was more extensive (Baldo et al., 2012; Rogalsky et al., 2015). In the context of this study, it may be that the pseudoword task elicited greater activation across all channels of interest; however, further work comparing the response of these regions to a real word task would be needed to confirm this inference.

[1]Seven control individuals with no history of speech/language impairment completed the same articulation task with 93.6% accuracy (SD=6). Accordingly, the patient error rates were within one standard deviation of this control sample.

In conclusion, our results support the contemporary models of motor speech (HSFC and DIVA) and demonstrate that the frontal and post-central cortices are strongly associated with motor speech control. Discrepancies regarding whether or not the insula is the cortical seat of speech production may be related to methodological issues across studies that either relied on lesion analyses in patients (for discussion, see Richardson et al., 2012) or functional magnetic resonance imaging (fMRI; Fedorenko et al., 2015; Moser et al., 2009; Wise et al., 1999). Due to natural divisions of the cerebral vasculature, the insula is highly susceptible to damage following a stroke affecting the middle cerebral artery, and it may be overrepresented in lesion analysis methods since it is often concurrently lesioned alongside crucial speech areas (Hillis et al., 2004; Kodumuri et al., 2016). Similarly, the sluggish temporal resolution of fMRI's blood-oxygenation related signal limits the ability to adjudicate whether insula activation is essential for speech production or may be related to other factors such as respiration and/or oral motor movements (Ackermann & Riecker, 2004; Ackermann & Riecker, 2010; Fedorenko et al., 2015). The use of ECoG allowed for investigation of the insula during speech production, without the potential confound of these factors. Nevertheless, the specific nature of the supportive role of the insula in speech should be tested by future studies.

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Highlights

- Direct cortical recordings of insula activity during speech production are reported
- Compared to the insula, frontal and post-central regions had greater activity during speech
- Results support contemporary models' emphasis on sensorimotor areas in speech production

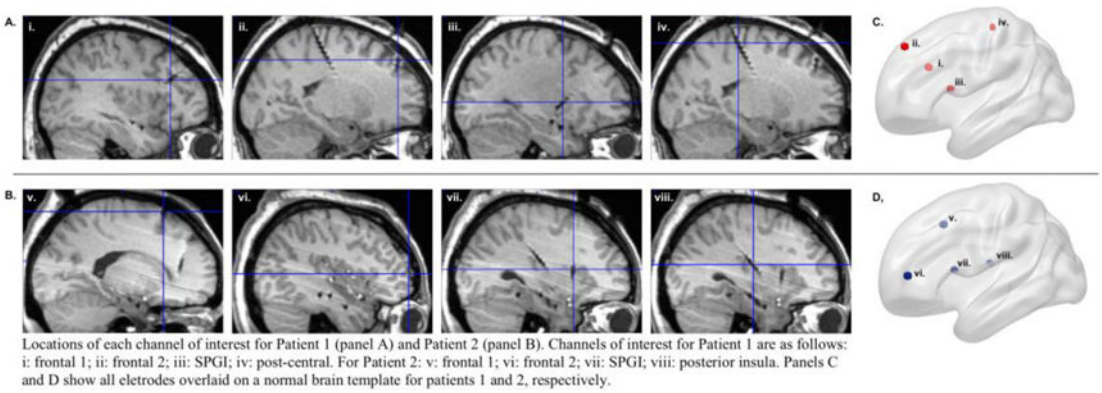

Figure 1.

Locations of each channel of interest for Patient 1 (panel A) and Patient 2 (panel B). Channels of interest for Patient 1 are as follows: i: frontal 1; ii: frontal 2; iii: SPGI; iv: post-central. For Patient 2: v: frontal 1; vi: frontal 2; vii: SPGI; viii: posterior insula. Panels C and D show all electrodes overlaid on a normal brain template for Patients 1 and 2, respectively.

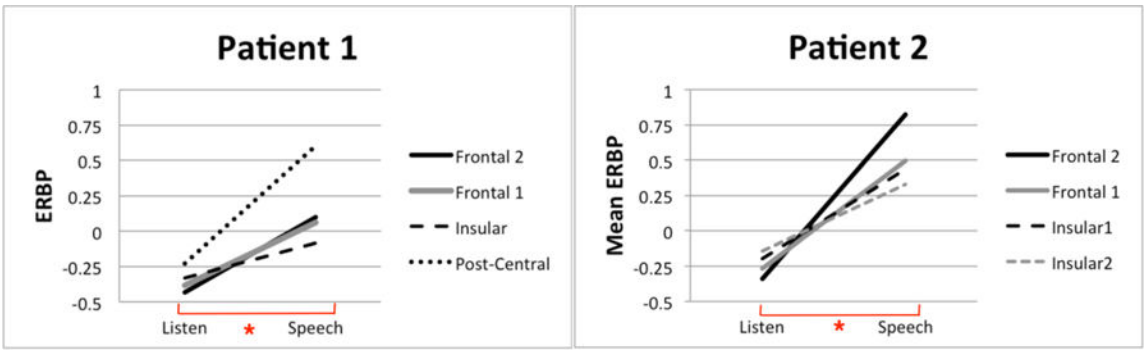

Figure 2.

Mean ERBP for each channel for the *Listen* and *Speech* conditions. Both figures illustrate the condition (*Listen v. Speech*) by channel interactions for both patients. The asterisk at the bottom of each figure indicates a significant difference between the *Listen* and *Speech* conditions.

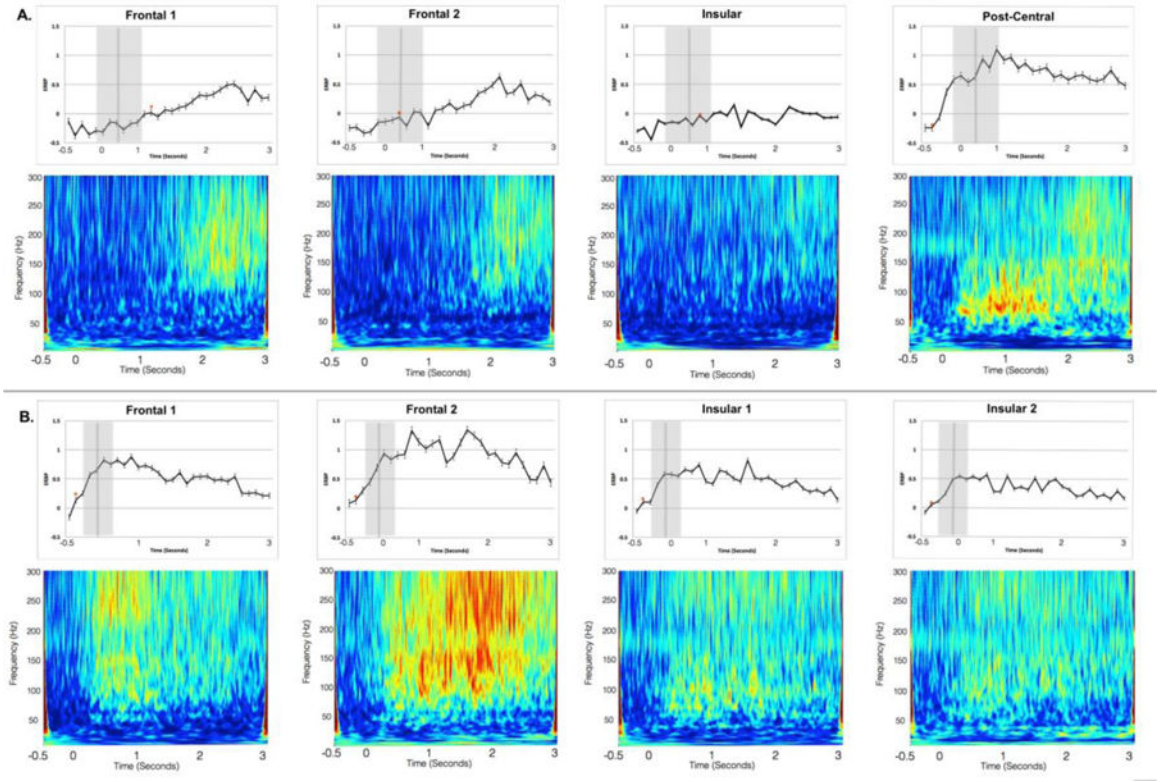

Figure 3.

Channel responses to the *Speech* conditions at each 100 ms time bin. Patient 1 data are presented in panel A, and Patient 2 in panel B. The 0 second time corresponds to the onset of the cue to produce speech, and the vertical grey bars correspond to the mean articulation latency from the cue to produce each target pseudoword (standard deviation indicated by the surrounding grey interval). The asterisks indicate the first time point in which ERBP for the *Speech* condition significantly exceeded that of the *Listen* condition. Spectrograms for each channel for the *Speech* conditions are presented below each time course figure; warmer colors (red, yellow) indicate higher activity across the three-second-response interval. The frequency bands of interest in this analysis are 75–150 Hz high gamma range.

Table 1

Anatomical coordinates for each channel of interest

Lobar Region	Anatomical Region	Patient	MNI Coordinate
Frontal 1	IFGpt	1	−36, 27, 25
Frontal 2	SFG	1	−21, 44, 44
Frontal 1	SFG	2	−17, 20, 65
Frontal 2	MFG	2	−40, 54, 6
Insular	SPGI	1	−29, 2, 4
Insular 1	SPGI	2	−30, 12, 10
Insular 2	Posterior insula	2	−31, −16, 15
Post-Central	PoCG	1	−20, −30, 60

Abbreviations: IFGpt: inferior frontal gyrus *pars triangularis*; SFG: superior frontal gyrus; MFG: middle frontal gyrus; SPGI: superior precentral gyrus of the insula; PoCG: post-central gyrus