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HIGH-GAMMA BAND FRONTO-TEMPORAL COHERENCE AS A MEASURE OF FUNCTIONAL CONNECTIVITY IN SPEECH MOTOR CONTROL

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Abstract—The neural basis of human speech is unclear. Intracranial electrophysiological recordings have revealed that high-gamma band oscillations (70–150 Hz) are observed in the frontal lobe during speech production and in the temporal lobe during speech perception. Here, we tested the hypothesis that the frontal and temporal brain regions had high-gamma coherence during speech. We recorded electrocorticography (ECoG) from the frontal and temporal cortices of five humans who underwent surgery for medically intractable epilepsy, and studied coherence between the frontal and temporal cortex during vocalization and playback of vocalization. We report two novel results. First, we observed high-gamma band as well as theta (4–8 Hz) coherence between frontal and temporal lobes. Second, both high-gamma and theta coherence were stronger when subjects were actively vocalizing as compared to playback of the same vocalizations. These findings provide evidence that coupling between sensory–motor networks measured by high-gamma coherence plays a key role in feedback-based monitoring and control of vocal output for human vocalization.

Key words: auditory cortex, premotor cortex, LFP, speech, efference copy, ECoG.

INTRODUCTION

Speech and language are uniquely human behaviors. The effort to define the neural circuits controlling normal and disordered speech has been limited largely to non-invasive techniques. However, in some cases direct recordings have been obtained from humans undergoing surgical treatment of medically intractable epilepsy. Because of the unique combination of temporal (i.e. milliseconds) and spatial (i.e. millimeters) resolution, these direct electrical recordings from the human cortex are particularly well-suited to investigate the neural bases of human speech.

One common pattern observed from areas that are required for language is oscillations in the high-gamma band. Specifically, high-gamma oscillations between 70 and 150 Hz are observed from inferior frontal gyrus during speech production (Flinker et al., 2010; Bouchard et al., 2013; Chang et al., 2013). Similar high-gamma oscillations have also been reliably observed in temporal cortical regions during auditory processing and in behavioral (i.e. vocal) compensation to feedback perturbation (Edwards et al., 2005; Greenlee et al., 2011, 2013). These results suggest the possibility that speech production centers in the frontal cortex interact with auditory and language processing centers in the temporal lobe (Garell et al., 2013), which would be consistent with current models of speech production (Guenther et al., 2006; Houde and Nagarajan, 2011).

Here, we test the hypothesis that frontal and temporal cortices interact via coherence in the high-gamma band as compared to the theta band. This idea predicts that high-gamma coherence should be modulated by vocalization. We studied this issue in five human patients undergoing surgery for treatment of medically intractable epilepsy. We report two new findings: (1) we observed specific high-gamma (70–150 Hz) coherence between the superior temporal gyrus (STG) and the frontal cortex, and (2) high-gamma coherence was stronger when subjects were actively vocalizing, particularly for contacts in the inferior frontal gyrus (IFG), as compared to playback conditions. These data provide insights into how frontal and temporal cortices interact to control speech production.

EXPERIMENTAL PROCEDURES

Subjects

Five males (ages 23–47 years, mean 32) from a larger pool of subjects undergoing surgical treatment of medically intractable epilepsy met criteria for this study. All subjects underwent pre-operative neuropsychological testing

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Abbreviations: CFC, cross frequency coupling; dPMC, dorsal premotor cortex; ERBP, event-related band power; HGE, hybrid depth electrode; IFG, inferior frontal gyrus; STG, superior temporal gyrus.

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which confirmed normal language functions. All subjects were right-handed with left-lateralized language hemispheric dominance based on pre-operative Wada testing. All subjects had left-sided frontal, temporal, and Heschl's gyrus recording electrodes. Written informed consent was obtained from every subject and all research protocols were approved by the University of Iowa Human Subjects Review Board. Experiments were conducted in a specially designed and electromagnetically-shielded private subject suite in the University of Iowa General Clinical Research Unit. Subjects did not incur any additional medical or surgical risks by participating in this study.

All subjects completed an extensive pre-surgical assessment which included a detailed neurological examination, brain imaging (MRI, PET, and SPECT), and a neuropsychological evaluation that confirmed normal speech and language functions. No anatomic lesions were observed in the cortical regions of interest to this study in any subject. Audiometric testing was conducted and all subjects were found to have normal hearing.

Electrode implantation

Detailed descriptions of the Heschl's gyrus hybrid depth electrode (HDE; Ad-Tech, Racine, WI, USA) used in this study and the methods of electrode implantation and subsequent anatomical localization of recording sites have been presented in earlier studies from our laboratory (e.g. Howard et al., 1996, 2000; Brugge et al., 2008; Reddy et al., 2010). HDEs were guided stereotactically (Stealth, Medtronic, Minneapolis, MN, USA) roughly parallel to the long axis of the left Heschl's gyrus. Each HDE carried four or six macro-contacts spaced 1 cm apart and 14 micro-contacts spanning the length of the HDE that consisted of 40-μm wires with exposed ends protruding 0.5 mm from the electrode shaft. Custom-manufactured high-density surface electrode arrays were also placed on the exposed peri-Sylvian and frontal and prefrontal cortex. The peri-Sylvian and frontal/prefrontal surface recording arrays consisted of 96 and 32 platinum–iridium disk electrodes, respectively, embedded within a silicon sheet (Ad-Tech, Racine, WI, USA). Inter-contact spacing for the peri-Sylvian arrays was a 5-mm center-to-center and 3-mm contact diameter. The frontal/prefrontal grids utilized a 10-mm center-to-center spacing. The exact position of the recording arrays differed somewhat between subjects as placement was based on subject-specific clinical considerations. In all subjects, the coverage provided by the arrays included significant portions of the lateral STG, including a previously described posterior lateral superior temporal auditory area (Howard et al., 2000). The electrodes remained in place during a 14-day hospital stay during which the subjects underwent continuous video-EEG monitoring. EEG monitoring confirmed that the cortical areas pertinent to this study did not show abnormal interictal activity. None of these areas were part of the epileptogenic focus and its eventual resection.

Electrode localization

The position of each recording electrode was localized using a combination of high-resolution digital photographs taken intra-operatively during electrode placement and removal, as well as thin-cut pre- and post-implantation MRI ($0.78 \times 0.78 \times 1.0$-mm voxel size) and CT ($0.45 \times 0.45 \times 1.0$-mm voxel size) scans. Pre- and post-implantation CT and MRIs were co-registered using a 3-D rigid-fusion algorithm implemented in FMRIB's Linear Image Registration Tool (Jenkinson et al., 2002). Coordinates for each electrode obtained from post-implantation MRI volumes were transferred to pre-implantation MRI volumes. The location of every contact relative to visible surrounding brain structures was compared in both pre- and post-implantation MRI volumes. The resultant electrode locations were then mapped to a 3-D rendering of the supratemporal plane for Heschl's gyrus electrodes and lateral surface for the grids. The estimated overall error in electrode localization using these techniques does not exceed 2 mm based on visual inspection.

Experimental design

Each experiment consisted of two blocks of vocalization and two blocks of listening to the playback of the same self-produced vocalizations. During the vocalization task, subjects were asked to maintain a steady vocalization of the vowel sound /a/ for approximately 2 s at their conversational pitch and volume. This vocal task was repeated 30–50 times during each block with subjects taking short breaks (1–2 s) between successive utterances and vocalizing at their own pace. A 10-dB gain (Mark of the Unicorn, Cambridge, MA, USA) was added to the voice signal such that this resultant auditory feedback signal would partially mask the effect of air-borne and bone-conducted feedback. At conversational levels, subjects maintained their voice volume at about 70–75 dB and received their feedback (through inset earphones) at 80–85 dB in vocalization blocks. Subjects wore earphones during the entire experiment.

Electrophysiological recording

Research recordings were initiated several days post-implantation after subjects had fully recovered from implantation surgery. The ECoG signals were simultaneously acquired with voice and feedback signals using a multi-channel data acquisition system (System3, Tucker-Davis Technologies, Alachua, FL, USA) under both vocalization and playback conditions. Electrodes were referenced to an extracranial subcutaneous electrode near the vertex. The ECoG signals were band-pass filtered (1.6–1000 Hz, -12 dB/octave anti-aliasing filter) and then digitized with a sampling frequency of 2034.5 Hz. Digitized data were then resampled offline at 2 kHz (MATLAB, Natick, MA, USA) for further processing.

ECoG data analysis

Recordings from all Heschl's gyrus and lateral grid electrodes were inspected to ensure they were not contaminated by epileptiform activity or artifact and