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Evaluating signal-correlated noise as a control task with language-related gamma activity on electrocorticography

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HIGHLIGHTS

- Forward speech activated frontal sites more than reverse speech and signal correlated noise (SCN).
- SCN activated temporal sites responding throughout stimuli less than forward and reverse speech.
- Sites of non-language-specific auditory activity were observed within Wernicke's region.

ABSTRACT

Objective: Our recent electrocorticography (ECoG) study suggested reverse speech, a widely used control task, to be a poor control for non-language-related auditory activity. We hypothesized that this may be due to retained perception as a human voice. We report a follow-up ECoG study in which we contrast forward and reverse speech with a signal-correlated noise (SCN) control task that cannot be perceived as a human voice.
Methods: Ten patients were presented 90 audible stimuli, including 30 each of corresponding forward speech, reverse speech, and SCN trials, during ECoG recording with evaluation of gamma activity between 50 and 150 Hz.
Results: Sites of the lateral temporal gyri activated throughout speech stimuli were generally less activated by SCN, while some temporal sites seemed to process both human and non-human sounds. Reverse speech trials were associated with activities across the temporal lobe similar to those associated with forward speech.
Conclusions: Findings herein externally validate functional neuroimaging studies utilizing SCN as a control for non-language-specific auditory function. Our findings are consistent with the notion that stimuli perceived as originating from a human voice are poor controls for non-language auditory function.
Significance: Our findings have implications in functional neuroimaging research as well as improved clinical mapping of auditory functions.

1. Introduction

Auditory language function is studied with a range of methodologies in humans (McNelly et al., 2009), including positron emission tomography (PET), functional magnetic resonance imaging (fMRI), near-infrared spectroscopy (NIRS), scalp electroencephalography (EEG), and magnetoencephalography (MEG). A well designed task to elicit cortical activity, including a control task to isolate task-specific activity, is critical. We previously attempted to validate reverse (or backward) speech as a control task in studies of auditory language with electrocorticography (ECoG) (Brown et al., 2012), the intracranial counterpart to EEG. In many fMRI studies, such time reversed speech is utilized to control for non-language-specific auditory activities (Gherri and Eimer, 2011; Moore-Parks et al., 2010; Perani et al., 1996; Redcay and

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Courchesne, 2008; Redcay et al., 2008; Sato et al., 2012). These studies commonly report that the blood-oxygen-level-dependent signal detected by fMRI is enhanced within peri-Sylvian regions during forward speech compared to reverse speech, supporting the notion that reverse speech controls for non-language-specific auditory functions. However, with ECoG we found that language-related activations of the temporal lobe, in particular those of the superior temporal gyrus with early-onset gamma (50–150 Hz) activity, showed similar or even greater augmentation during reverse speech compared to forward speech (Brown et al., 2012). Taking into account that gamma-augmentation is generally considered as an excellent summary measure of cortical activation (Kojima et al., 2013; Lachaux et al., 2012; Ray et al., 2008), this ECoG observation suggests that reverse speech is a rather poor control for non-language-specific auditory activity in the brain. We hypothesized that the problem lies in the fact that reverse speech is still perceived as originating from a human voice, although it is largely unintelligible.

Various other types of control tasks have also been described in the literature and used for similar purposes. Several of these can be generated to match normal speech sounds for certain characteristics, such as duration or amplitude envelope, but do not retain those essential to create the perception of a human voice. These are considered as non-speech sounds. Noise-vocoded speech is essentially a normal speech signal with reduced spectral complexity generated by restricting the output sound to a finite set of frequency components without altering the amplitude envelope (Davis and Johnsrude, 2003; Millman et al., 2011; Shannon et al., 1995). Noise-vocoded speech shows the curious effect of enhancing the blood-oxygen-level-dependent signal on fMRI relative to normal speech when the degree of frequency degradation is not severe (Davis and Johnsrude, 2003), such as when a great number of frequency bands are utilized to reconstruct the speech. Musical rain can be generated from frequency formants otherwise used to produce synthetic voice sounds but with a randomly varying carrier frequency and formant onset to produce a rapid spatter of 'pips' with a pleasant, rain-like quality (Uppenkamp et al., 2006). Signal-correlated noise (SCN) is essentially a noise signal that is modulated by the amplitude envelope of the original speech signal (Davis and Johnsrude, 2003; Schroeder, 1968). Both musical rain and SCN have been shown on fMRI to activate superior temporal regions less robustly than normal speech sounds, suggesting them to be possible controls for non-language-specific auditory function.

We set out to determine whether a sound that did not create the perception of a human voice may better control for non-language-specific auditory activty as measured on ECoG in the temporal lobe compared to reverse speech. We chose to test SCN because it can be generated directly from the original forward speech sound (Davis and Johnsrude, 2003). Like reverse speech, SCN retains the exact same duration and intensity. However, unlike reverse speech, SCN is not perceived as a human voice. While reverse speech does retain some potential for intelligibility (Cowan et al., 1982), SCN cannot be understood in any circumstance (Davis and Johnsrude, 2003).

In our previous study comparing ECoG activities associated with forward and reverse speech, we noted two distinct sub-classes within the class of sites showing augmentation of gamma activity during auditory stimuli (Brown et al., 2012). In one sub-class, gamma-augmentation was restricted to only the earliest portions of the auditory stimulus. In the other sub-class, gamma-augmentation extended throughout the stimulus from beginning to end. In this follow-up study, we distinguished these sub-classes as 'Early Auditory' and 'Full Auditory' and analyzed them separately. We tested the following hypotheses for ECoG sites of the temporal lobe: (1) ECoG sites with augmented gamma activity spanning the entire duration of an auditory stimulus (i.e.: 'Full Auditory' sites) will show enhanced augmentation during reverse speech compared to forward speech and reduced augmentation during SCN. Such sites are responding to the entirety of the language stimuli and may be involved in the initial extraction of language-related auditory information prior to semantic processing. (2) ECoG sites with augmented gamma activity occurring only very early during an auditory stimulus (i.e.: 'Early Auditory' sites) will not show any preference for sounds perceived as human speech. Because these sites show only brief auditory responses upon stimulus delivery, they are not likely to be involved in the extraction of language-related auditory information.

2. Materials and methods

2.1. Study patients

Patients were selected by using the following inclusion criteria: (i) a history of intractable focal epilepsy scheduled for extraoperative subdural ECoG recording as part of presurgical evaluation at Children's Hospital of Michigan or Harper University Hospital, Detroit, between December 2011 and March 2013, (ii) age of 5 years or older, and (iii) measurement of ECoG amplitude augmentations driven by a language task described in Section 2.3. Our ECoG study performed prior to the current study period reported that even a 4-years-old child cooperatively and accurately named objects in an auditory-naming task and naming-related gamma-augmentation was observed in both temporal and frontal regions (Kojima et al., 2013).

Exclusion criteria consisted of: (i) presence of massive brain malformations (such as large perisylvian polymicrogyria or hemimegalencephaly) which confound anatomical landmarks for the central sulcus and Sylvian fissure, (ii) history of hearing impairment, (iii) right language dominance as determined by Wada testing (i.e. intracarotid sodium amobarbital procedure) or left-handedness when Wada test results are not available (Knecht et al., 2000), (iv) multiple seizure foci involving both hemispheres, (v) Verbal Comprehension Index (VCI) or Verbal Intelligence Quotient (VIQ) less than 70, (vi) inability to complete the language task described in Section 2.3 due to lack of adequate vocabulary or cooperation, and (vii) history of previous neurological surgery. We studied a consecutive series of 10 patients satisfying all criteria (age range: 5–30 years; five females; Table 1). This study has been approved by the Institutional Review Board at Wayne State University, and written informed consent was obtained from all patients or their legal parent or guardian.

Subdural platinum grid electrode (10 mm inter-contact distance; 4 mm diameter) placement was as described previously by our team (Kojima et al., 2013). Extraoperative video-ECoG recordings were obtained for 3–5 days, using a 192-channel Nihon Kohden Neurofax 1100A Digital System (Nihon Kohden America Inc., Foothill Ranch, CA, USA) at a sampling frequency of 1000 Hz as previously described (Kojima et al., 2013). Total electrode contact number ranged from 86 to 128 (Table 1). Seizure onset zones were clinically determined (Asano et al., 2009a) and excluded from subsequent analysis.

2.2. Coregistration of electrodes on individual three-dimensional MRI

MRI, including a volumetric T1-weighted spoiled gradient echo image as well as fluid-attenuated inversion recovery image of the entire head, was obtained preoperatively using a previously described protocol (Nagasawa et al., 2010a). Planar X-ray images (lateral and antero-posterior) were acquired with subdural electrodes in place for localization on the brain surface; three metallic fiducial markers at anatomically well-defined locations aided