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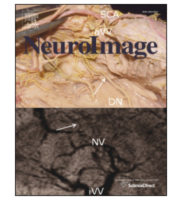

Spatial and temporal relationships of electrocorticographic alpha and gamma activity during auditory processing

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ABSTRACT

Neuroimaging approaches have implicated multiple brain sites in musical perception, including the posterior part of the superior temporal gyrus and adjacent perisylvian areas. However, the detailed spatial and temporal relationship of neural signals that support auditory processing is largely unknown. In this study, we applied a novel inter-subject analysis approach to electrophysiological signals recorded from the surface of the brain (electrocorticography (ECoG)) in ten human subjects. This approach allowed us to reliably identify those ECoG features that were related to the processing of a complex auditory stimulus (i.e., continuous piece of music) and to investigate their spatial, temporal, and causal relationships. Our results identified stimulus-related modulations in the alpha (8–12 Hz) and high gamma (70–110 Hz) bands at neuroanatomical locations implicated in auditory processing. Specifically, we identified stimulus-related ECoG modulations in the alpha band in areas adjacent to primary auditory cortex, which are known to receive afferent auditory projections from the thalamus (80 of a total of 15,107 tested sites). In contrast, we identified stimulus-related ECoG modulations in the high gamma band not only in areas close to primary auditory cortex but also in other perisylvian areas known to be involved in higher-order auditory processing, and in superior premotor cortex (412/15,107 sites). Across all implicated areas, modulations in the high gamma band preceded those in the alpha band by 280 ms, and activity in the high gamma band causally predicted alpha activity, but not vice versa (Granger causality, $p < 1e^{-8}$). Additionally, detailed analyses using Granger causality identified causal relationships of high gamma activity between distinct locations in early auditory pathways within superior temporal gyrus (STG) and posterior STG, between posterior STG and inferior frontal cortex, and between STG and premotor cortex. Evidence suggests that these relationships reflect direct cortico-cortical connections rather than common driving input from subcortical structures such as the thalamus. In summary, our inter-subject analyses defined the spatial and temporal relationships between music-related brain activity in the alpha and high gamma bands. They provide experimental evidence supporting current theories about the putative mechanisms of alpha and gamma activity, i.e., reflections of thalamo-cortical interactions and local cortical neural activity, respectively, and the results are also in agreement with existing functional models of auditory processing.

Introduction

Music is a perceptual experience that engages many cognitive processes within different regions of the brain (Stewart et al., 2006). Over the past few decades, numerous studies using hemodynamic and electrophysiological imaging techniques (fMRI/PET and EEG/MEG, respectively) have attempted to uncover the neural underpinnings of music processing. For instance, a recent fMRI study by Alluri et al., 2012 investigated the BOLD responses related to the processing of timbre, rhythm, and tone while subjects listened to music. Other neuroimaging studies investigated the relationship between sound intensity and brain activity in auditory cortex (Brechmann et al., 2002; Hart et al., 2003; Mulert et al., 2005; Tanji et al., 2010; Thaerig et al., 2008; Yetkin et al., 2004), and EEG studies determined relationships between rhythm and pitch and EEG components during listening and imagination of melodies (Schaefer et al., 2009).

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These and other studies have made important progress in identifying those brain regions whose activity changes with the perception of different individual musical features (e.g., sound intensity, rhythm, pitch), but most of them have been constrained to highly controlled experiments using artificial stimuli (e.g., presenting tones at different intensities or pitches). This is unfortunate, because cortical processing of artificial stimuli may differ in important ways from the processing of complex natural stimuli (such as music), and because evidence suggests that the brain employs general principles that govern the processing of complex natural stimuli (Hasson et al., 2004, 2010). In addition to experimental constraints, methodological limitations have not allowed to simultaneously evaluate the temporal and spatial dynamics related to music processing. For instance, fMRI and PET measure brain metabolic activity with excellent spatial but reduced temporal resolution (several seconds). Thus, they cannot track the rapid moment-to-moment variations related to processing of continuous music. Conversely, EEG and MEG measure brain electrical activity with excellent temporal resolution but poor spatial resolution (several centimeters) and cannot reliably ascribe activity changes to particular brain areas.

Electrocorticographic (ECoG) recordings from the surface of the brain have recently been used to study the neural dynamics during processing of complex sounds, in particular speech (Edwards et al., 2009; Lachaux et al., 2007; Pasley et al., 2012; Sinai et al., 2009). This relatively new imaging technique combines high temporal resolution with high spatial resolution and coverage. It can also detect different neurophysiological processes that subserve sensory, motor/language, or cognitive functions (Crone et al., 1998; Hermes et al., 2011). These processes include ECoG modulations in the alpha (8–12 Hz) and high gamma (70–110 Hz) frequency bands. Activity in the alpha band seems to reflect interactions between the thalamus and the cortex (Lopes Da Silva, 1991; Steriade et al., 1990; Zhang et al., 2004), and may facilitate information transfer to task-related cortical areas by inhibiting neural activity in task-unrelated areas (Jensen and Mazaheri, 2010). On the other hand, activity in the high gamma band seems to reflect task-related activity of neural populations directly underneath the electrodes (Crone et al., 1998, 2001; Miller et al., 2007, 2009; Schalk et al., 2007).

Despite this body of work, the most salient spatial and temporal relationships of these neural processes during processing of a complex natural auditory stimulus remain undefined. To address this issue, we recorded electrical activity from electrodes implanted on the brain's surface of ten human subjects while they were listening to music. We used these data to define the cortical locations that modulate their alpha or gamma activity during auditory processing and to define their temporal and causal relationships. Our results implicate perisylvian structures as well as superior premotor cortex, and establish the differing spatial and temporal contributions of alpha and gamma activity.

Materials and methods

Subjects and data collection

We recorded electrical activity from intracranial electrodes of ten subjects (4 men, 6 women) with intractable epilepsy who were listening to a complex natural auditory stimulus (the song “Another Brick in the Wall — Part 1” (Pink Floyd, Columbia Records, 1979)). These subjects underwent temporary implantation of subdural electrode arrays to localize the epileptogenic focus and to delineate it from eloquent (i.e., functional) cortical areas prior to brain resection. Table 1 summarizes the subjects' clinical profiles. All of the subjects gave informed consent to participate in the study, which was approved by the Institutional Review Board of Albany Medical College. None of the subjects had a history of hearing impairment. The implanted electrode grids consisted of platinum-iridium electrodes that were 4 mm in diameter (2.3–3 mm exposed) and spaced with an inter-electrode distance of 0.6 or 1 cm. The total numbers of implanted electrodes were 96, 83, 109, 58, 120, 58, 59, 98, 134, and 98 for the different subjects, respectively. Electrodes were implanted on the left hemisphere for all subjects (see Fig. 1 for electrode coverage). ECoG signals were digitized at 1200 Hz, synchronized with stimulus presentation, and stored using the BCI2000 software platform (Schalk and Mellinger, 2010; Schalk et al., 2004). ECoG signals were recorded while the subjects were listening to the song, which was 3:00 min long, digitized at 44.1 kHz in waveform mono audio file format, and binaurally presented to each subject using in-ear monitoring earphones. In addition, we recorded the same amount of ECoG signals while subjects were at rest with eyes open. We visually inspected the recordings and removed those electrodes that did not contain clean ECoG signals or had interictal activity, which left 86, 82, 103, 56, 108, 57, 53, 93, 110, and 92 electrodes for the different subjects.

Table 1
Clinical profiles of the subjects that participated in the study. All of the subjects had normal cognitive capacity and were functionally independent.

Subject	Age	Sex	Handedness	Seizure Focus	# of Elec.
A	29	F	R	Left temporal	86
B	30	M	R	Left temporal	82
C	26	F	R	Left temporal	103
D	45	M	R	Left temporal	56
E	29	F	R	Left temporal	108
F	45	F	L	Left temporal	57
G	60	M	R	Left temporal	53
H	17	F	L	Left temporal	93
I	28	M	R	Left temporal	110
J	25	F	R	Left temporal	92

Cortical mapping

We defined the brain anatomy of each subject using pre-operative magnetic resonance imaging (MRI) scans, and the location of the electrodes using post-operative computer tomography (CT) imaging. We then created a 3D surface model of each subject's cortex from the MRI images, co-registered it with the location of the electrodes given by the CT images using Curry Software (Compumedics NeuroScan), and transformed the 3D model and electrode locations into Talairach space (see Fig. 1).

Extraction of ECoG and sound features

To extract the time course of alpha and high gamma activity, we first filtered ECoG signals from each electrode at each specific frequency band (i.e., 8–12 Hz and 70–110 Hz) using an IIR band-pass filter and removed spatially distributed noise common to all ECoG electrodes using a common average reference (CAR) spatial filter. We then computed the envelope of the ECoG signal (i.e., the magnitude of the analytic signal) in each frequency band. Finally, we computed the natural logarithm of the envelope power (i.e., squaring each element of the envelope and then computing the natural logarithm) and resampled the result to 10 Hz. To extract the song's sound intensity, we computed the average power derived from non-overlapping 10 ms segments of the song. We then smoothed the sound intensity by applying a low pass IIR filter at 5 Hz and resampled the result to 10 Hz. The total length of the alpha, high gamma, and sound intensity time courses are 1800 samples each. All filtering operations were performed forwards and then backwards (using Matlab's filtfilt command) to avoid an introduction of a group delay. The following analyses then determined those locations or interactions across locations that contained alpha or gamma activity that was related to auditory processing.

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