Concurrent EEG/fMRI of Temporal Fluctuations in the 40-Hz Auditory Steady State Response

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Introduction. Concurrent recording of event-related potentials (ERP) with functional MRI (fMRI) is an emerging tool in functional neuroimaging with the potential to reveal new mechanisms for cognitive and sensory phenomena by taking advantage of the complementary spatiotemporal resolutions of the two techniques [1]. Concurrent, rather than separate, recordings are important since concurrent recordings allow for the detection of temporal covariances between the two modalities [2], and since concurrent recordings eliminate environmental disparities present in separate recordings. One important ERP is the 40-Hz auditory steady-state response (ASSR), which has been related to thalamo-cortical function and loss of consciousness [3]. In this study we describe methods for recording 40-Hz ASSR during fMRI and demonstrate that temporal fluctuations in the ASSR correlate with fMRI activity throughout the auditory system, from brainstem to cortex.

Materials and Methods. A total of 11 normal healthy volunteers were studied, with 2-4 runs per subject. Images were taken using clustered-volume acquisition at 3T, with cardiac gating in 7 subjects. Functional MRI acquisitions were arranged according to a "Long-TR" auditory fMRI design, with volume acquisition in 1 second (15 4mm slices 1mm skip, coronal orientation) and spaced ~9-seconds apart, allowing hemodynamic responses elicited by acoustic scanner noise to subside before the next volume acquisition [4]. EEG acquisitions were interleaved between image acquisitions using a custom-made 24-bit electrophysiological recording system with high dynamic range to prevent saturation during imaging (1-kHz sampling rate; DC to 500-Hz bandwidth). EEG electrodes were placed in adjacent bipolar pairs along a coronal plane (M2->T8, T8->C6, C6->C4, C4->Cz, Cz->C3, C3->C5, C5->T7, T7->M1), with resistive carbon fiber leads to prevent SAR increases [5]. Motion sensors were placed above pre-auricular points for motion-artifact rejection [6]. Stimuli consisted of 1-msec clicks at 40-Hz in a 30-sec ON/OFF pattern, for a total of 15 minutes per run, delivered by a laptop running Presentation 0.76 (Neurobehavioral Systems) and a custom-built electrically-shielded electrostatic headphone system with frequency response to 20 kHz and acoustic noise attenuation of >30 dB above 800 Hz.

ASSRs were computed from a linear combination of channels from M2->Cz in the frequency domain using multi-taper spectral analysis [7] (bandwidth = 0.4 Hz) from 4-second windows centered 4-seconds prior to each volume acquisition. This arrangement reflects the widely-observed phenomenon that the BOLD hemodynamic delay from stimulus onset is approximately 4-seconds [4]. Equivalently, fMRI BOLD signals represent neural activity predominantly from events 4-seconds prior to an fMRI volume acquisition. For each window, the amplitude (square-root of power) at 40-Hz was computed to produce a 40-Hz amplitude time-series. The fMRI data were then analyzed with a linear model consisting of the 40-Hz amplitude time series (main effect) plus a 6th-order polynomial (nuisance effect), fitted using AFNI 3dDeconvolve [8].

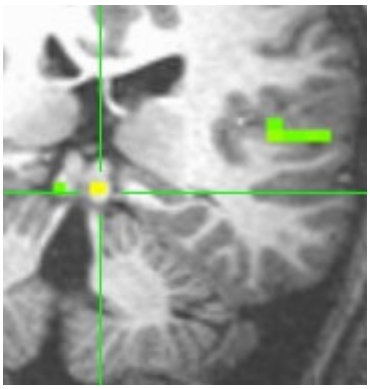

Figure 1. Subject "A", activity in IC and HG.

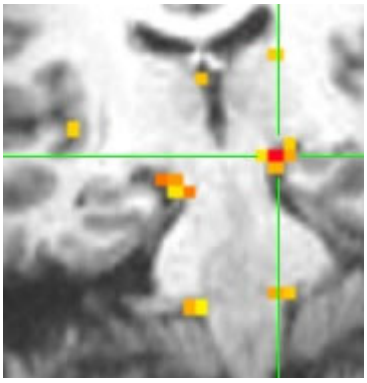

Figure 2. Subject "B", activity in CN, MGN, and

Results and Discussion. The 40-Hz amplitude time series displayed temporal fluctuations correlated with fMRI time series throughout the auditory system, including cochlear nucleus (CN), inferior colliculus (IC), medial geniculate nucleus (MGN), and Heschel's gyrus (HG). Figures 1 and 2 show BOLD fMRI activity (F-statistic, P<0.001) from two different subjects, revealing activity in HG and IC in Subject A, and CN, MGN, and HG in Subject B, respectively. Figures 3 and 4 show the time series fits from the IC of Subject A and the MGN of Subject B, respectively, showing the correspondence between 40-Hz ASSR amplitude and fMRI BOLD response. The voxel time series correspond to the crosshairs displayed in Figures 1 and 2.

Conclusions. We have demonstrated that time-varying ERP measurements can be made concurrently with fMRI, and that these time-varying measurements can be correlated with the BOLD signal at 3 Tesla. With this paradigm, we have shown that temporal fluctuations in the 40-Hz ASSR are represented throughout the auditory system from brainstem to cortex, challenging the view that the 40-Hz ASSR is predominantly a cortical phenonmenon.

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