Neuroelectrical Decomposition of Spontaneous Brain Activity Observed with Functional Magnetic Resonance Imaging

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Purpose Resting state fMRI has been the primary imaging tool to study functionally specialized neural networks. However, the fMRI signal averages contributions from a multitude of neuronal processes that may emerge and travel along distinct neural pathways. It may not be able to separate a confluence of functionally distinct yet spatially and temporally overlapping networks. To address this particular issue, we propose a novel subspace analysis method that jointly considers fMRI and electroencephalography (EEG) data. This method is based on the notion that the neuroelectric activity underlying the fMRI signal may have EEG spectral features that report on regional neuronal dynamics and inter-regional interactions. We hypothesize that such spectral signatures would not only offer a new way to parcel the resting brain into spectrally defined clusters but also help disentangle the involvement of brain regions within and across overlapping functional networks.

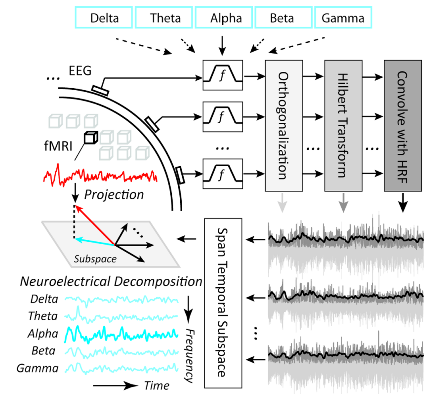

Figure 1. Subspace analysis method for EEG-fMRI

Methods Concurrent EEG and fMRI, acquired from 15 subjects during a 10-minute eyes-closed resting state, were jointly analyzed with the new subspace projection method. Briefly, the band-limited power (BLP) was extracted from all EEG sensors and used to span a temporal subspace, onto which the fMRI signal at every voxel was projected (Fig. 1). To generate this subspace, the band-pass filtered signals were extracted from five frequency bands covering the classical delta, theta, alpha, beta and gamma ranges. To un-mix signals between sensors due to the volume conduction effect, the band-pass filtered signals were first orthogonalized across sensors for each frequency band separately. We extracted the power envelopes from the orthogonalized signals and then, for each frequency band, created a temporal subspace based on the strongest principal components contributing to these signals. This subspace was further convolved with the hemodynamic response function (HRF), after which we projected each voxel's fMRI signal separately onto each frequency-band-specific subspace. As a result, the fMRI signal was decomposed into five component time-series signals, each of which was associated with one of the five EEG frequency bands. Subsequently, we evaluated how resting state fMRI signals and their inter-regional correlations depended on individual EEG frequency components.

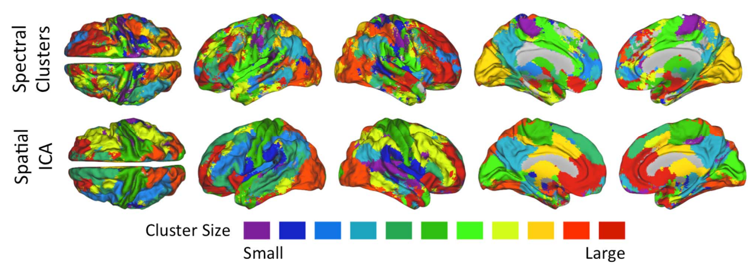

Figure 2. Spectrally vs. spatially informed parcellation of brain regions

Results For each voxel, we derived a spectral signature describing the differential contributions of individual EEG frequency bands to the variance of local fMRI signal. We parceled the grey matter into 11 divisions by grouping the voxel-wise spectral signatures with the *k*-means clustering algorithm. Such spectrally distinct clusters were well organized and resembled those found based on the spatial ICA analysis of fMRI data (Fig. 2). We also computed the seed-based correlation of the fMRI signals projected onto each frequency specific subspace. For example, when a seed voxel was selected in the left auditory cortex, the functional connectivity was frequency dependent in a manner that varied across voxel pairs. In contrast, when the fMRI data were analyzed without considering the EEG, the observed correlation pattern compounded the contributions of multiple underlying networks with distinct spectral features. Applying the k-means clustering to the spectral features of functional connectivity, we sub-divided the correlation pattern into two spectrally distinct clusters: one dominated by the lower frequency bands and the other by the higher frequency bands (Fig. 3).

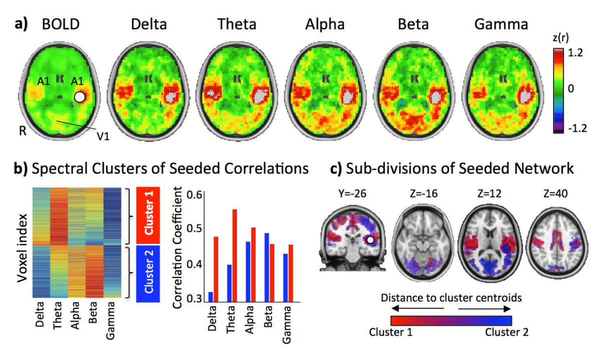

Figure 3. a) The seed-based correlation maps with the seed ROI in left A1 (shown on the right size of the image), based on either the original BOLD signals or the component BOLD signals associated with distinct frequency bands. b) Two spectral clusters of the seeded correlations. The color matrix shows the relative correlation strength across frequency bands for the voxels resorted by clusters. The bar charts show the mean spectral profile of the absolute correlation coefficients averaged within the first (red) and second (blue) clusters. c) The spatial distribution of the two sub-divisions of the A1-seeded correlation map, color-coded by the distance to the centroid spectral profiles of the two clusters.

Discussion The integrated EEG-fMRI approach allowed decomposition of the fMRI voxel time-series into multiple components with distinct EEG spectral correlates. This led to a novel interpretation of spontaneous brain activity and functional connectivity in the presence of overlapping neural networks with distinct spectral characteristics. It was found: 1) Regional BOLD signals receive differential contributions from individual frequency components of underlying neuroelectric signals, with a spectral signature that varies across brain regions. 2) This spectral signature allows for the grouping of brain regions into functional clusters, some of which resembled functional networks extracted from fMRI data with conventional analysis methods. 3) Inter-regional fMRI signal correlations are also frequency dependent, which allows dividing a seed-based functional network into multiple sub-networks with distinct spectral properties.

Conclusion This approach expands fMRI by adding one dimension representing the frequency of neuroelectric activity. This additional information will allow frequency tags to be placed to distinct neuronal components of the fMRI signal, allowing for the probing of spectral decomposition of regional and network neural activity as well as the spatiotemporal imaging of neuroelectric oscillations driven either externally by stimulation or internally through self-organized neural systems.