A Spatiotemporal Signal Space Projection Method for Artifact Reduction in Simultaneous EEG-fMRI Acquisitions

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Introduction

When acquiring simultaneous EEG-fMRI data, there can be significant artifacts in the EEG data due to MR gradients, cardiac pulsations, and other interference sources from outside the brain. Although some of these artifacts can be greatly reduced using template based subtractions [1,2], residual artifacts typically persist. The residual artifacts can be removed with component-based methods, such as principal components analysis (PCA) and independent components analysis (ICA), but these methods require human intervention to reject the appropriate components or are unable to adequately isolate the artifact. In this abstract, we introduce a spatiotemporal signal space projection (SSP) method to remove the residual artifacts without user intervention. The basic idea behind the SSP approach for spatial filtering has been previously described [3], but has not yet been applied to EEG-fMRI data. In addition we extend the method to include a temporal filtering step that further decreases the residual artifacts.

Theory

The basic idea behind the method is that the "true" EEG signal lies in a subspace spanned by the EEG lead field matrix (LFM), which maps neuronal dipole sources in the brain to EEG electrode space. This signal subspace has a dimension equal to the number of EEG electrodes, but can be represented sufficiently well using a lower dimensional basis set. Projecting the EEG signal onto the LFM subspace is the first step in removing residual artifacts. To further reduce the artifacts we identify the portion of the EEG signal that is orthogonal to the LFM subspace and at the frequency of the expected gradient artifacts. We then project this component out of the data. The EEG signal model at time t is given by $\mathbf{y} = \mathbf{A}\mathbf{x} + \boldsymbol{\varepsilon}$, where $\mathbf{y}$ is the EEG channel data vector, $\mathbf{A}$ is the LFM (not dependent on t), $\mathbf{x}$ is a vector of neuronal dipole moments and $\boldsymbol{\varepsilon}$ is noise/interference. From the signal model we note that the neuronal signal of interest lies in the column space of $\mathbf{A}$, for which we find an orthonormal basis using singular value decomposition (SVD). We choose a subset of the basis that explains 99.9% of the variance of the LFM column space (high enough to be sensitive to true neuronal sources but allows for artifact rejection) and form a matrix $\mathbf{U}$ from that subset. The spatial projection matrix is then defined as $\mathbf{P}_\mathbf{A} = \mathbf{U}\mathbf{U}'$ where $'$ denotes matrix transpose. The projected EEG signal for true neuronal sources is $\mathbf{y}_s = \mathbf{P}_\mathbf{A}\mathbf{y}$ and the artifact signal is $\mathbf{y}_a = (\mathbf{I} - \mathbf{P}_\mathbf{A})\mathbf{y}$. To take out any gradient artifact induced temporal variation the projection $\mathbf{P}_\mathbf{A}$ may introduce, we build a new projection matrix based on the row space of a matrix $\mathbf{Y}_a$, with the t-th column defined as $\mathbf{y}_a$ at time t. The rows are bandpass filtered to isolate the temporal component at the fundamental frequency of the gradient artifacts, i.e., the inter-slice frequency of the MRI acquisition. We use SVD to find an orthonormal basis for the row space and choose a subset that explains 95% of the variance to capture the temporal based artifact. We then form a matrix $\mathbf{V}$ with that subset and project out the remaining artifact components to obtain the denoised signal $\mathbf{Y}_{st} = \left(\left(\mathbf{I} - \mathbf{V}\mathbf{V}'\right)\mathbf{Y}_a{}'\right)'$.

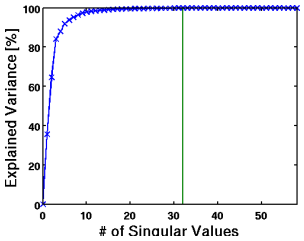

Figure 1: Cumulative % explained variance with line indicating 99.9%

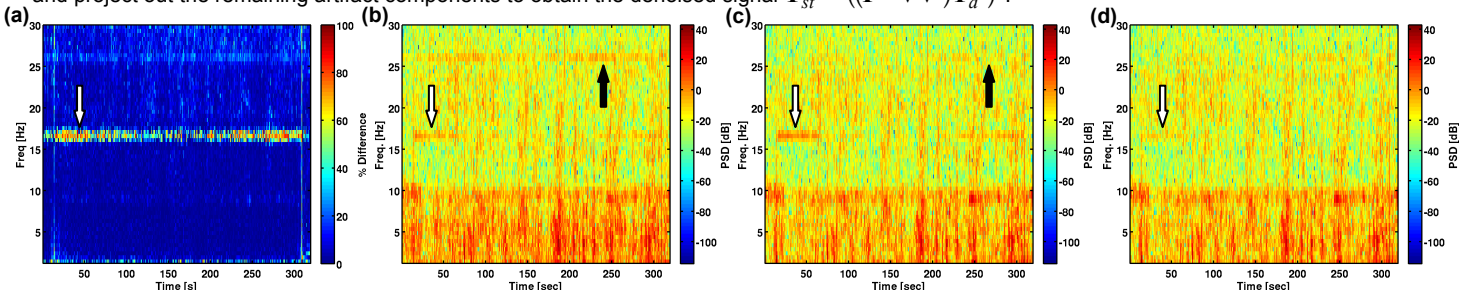

Figure 2: (a) Percent reduction in PSD after spatiotemporal projection (averaged over all channels); PSD for one channel (b) before projection, (c) after spatial projection and (c) after temporal projection.

Methods

The fMRI data were collected on a 3T GE MR750 scanner, with inter-slice timing of 60ms and the EEG data were collected using a 64 channel MRI-compatible EEG system (BrainAmp MR Plus; Brain Products GmbH). We analyzed one run from one subject and used a high resolution anatomical scan and Freesurfer software to define dipole locations spaced 7mm apart at the gray/white matter boundary, resulting in 6407 dipoles. We then used NFT software [4] to build the LFM. MR gradient and cardio-ballistic artifacts were removed with a template based subtraction method. EEGLAB [5] was then used to reject faulty channels (resulting in retention of 58 out of 64 channels) and time segments with excessive movement artifact. The data were bandpass filtered from 1-30Hz before projecting out the artifacts using the method described in the Theory section.

Results and Discussion

Figure 1 shows the percent variance explained in the LFM column space by the singular values, with the line indicating that 99.9% of the variance is explained with 32 singular values. Figure 2(a) shows the percent reduction in Power Spectral Density (PSD) averaged across all channels that is obtained with the proposed method. The arrow shows where there is a clear reduction at the fundamental frequency of the residual gradient artifacts. Figure 2(b)-(c) shows the PSD for one channel before using the proposed method, after the spatial projection, and after the temporal projection. In Figure 2c, the black arrow indicates an artifact band that is removed from this channel after using the spatial projection, while the white arrow points to a residual gradient artifact that is still present. This artifact is then removed in the temporal projection (see Fig 2d). In summary, the proposed spatiotemporal projection method has been shown to be effective for the removal of residual artifacts and should prove to be useful for a wide range of simultaneous EEG-fMRI studies.

References: [1] Allen et. al., *Neuroimage* 1998, 8:229-239. [2] Allen et. al., *Neuroimage* 2000, 12:230-239. [3] Uusitalo et. al., *Med Biol Eng Comput* 1997, 35:135-140. [4] http://sccn.ucsd.edu/nft/. [5] http://sccn.ucsd.edu/eeglab/