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Signal Processing Challenges for Single-trial Analysis of Simultaneous EEG/fMRI

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Abstract— **A relatively new neuroimaging modality is simultaneous EEG and fMRI. Though such a multi-modal acquisition is attractive given that it can exploit the temporal resolution of EEG and spatial resolution of fMRI, it comes with unique signal processing and pattern classification challenges. In this paper I will review some our work at developing signal processing and pattern recognition for analysis of simultaneous EEG and fMRI, with a focus on those algorithms enabling a single-trial analysis of the neural signal. In general, these algorithms exploit the multivariate nature of the EEG, removing MR induced artifacts and classifying event-related signals that then can be correlated with the BOLD signal to yield specific fMRI activations.**

I. INTRODUCTION

EEG offers millisecond temporal resolution, however the spatial sampling density and ill-posed nature of the inverse model problem limit its spatial resolution. On the other hand, fMRI provides millimeter spatial resolution, but due to scanning rates and the low-pass nature of the BOLD hemodynamic response, the temporal resolution is rather limited. These imaging modalities could clearly complement each other particularly if simultaneous acquisition of the EEG and fMRI can be achieved.

Major technical challenges for simultaneous acquisition include 1) removal of large magnetic field gradients and radio frequency (RF) pulses used to produce the MR images from the EEG [1], 2) special EEG amplifier design to remove the DC components without allowing the gradients to saturate the input stage [2], 3) novel EEG electrode design to minimize artifact formation [1], [3], 4) removal of cardiac-related artifacts (ballistocardiogram) [1], [4], and 5) removal of motion artifacts in the EEG which are usually amplified when subjects are placed in an MR scanner [5].

Several investigators have already explored the possibility of combining EEG with fMRI by considering near-simultaneous acquisition. For instance, they used interleaved acquisition [6], [7], [8] or fMRI following inter-ictal spikes [9], [10], [11], techniques that result in protocol limitations and problems with data analysis. Others have focused on the specific problem of how fMRI can be used to constrain the localization of sources computed via the EEG-scalp projections in order to provide better localization of the electrical dipoles [12], [13], [14]. These approaches however rely heavily on trial or event-locked averaging and therefore the inter-trial variability, which is critical for understanding the relationship between the neuronal responses and behavior, is concealed.

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In a recent study, Benar et al [15] used simultaneous EEG/fMRI to look at trial-to-trial variability in P300 amplitude and latency for an auditory oddball paradigm. By low-pass filtering the EEG data at 8 Hz, they identified cortical areas whose hemodynamics co-varied, both positively and negatively, with trial-to-trial variability with P300 latency and amplitude. While isolating brain activity related to gross P300 amplitude and latency variability is informative, filtering the EEG data at such a low frequency removes significant event-related signal that enables more detailed decomposition of the timing information in the EEG. In addition, their fMRI analysis focused on variations in a single electrode (Cz).

Multivariate analysis of the EEG, for example via independent component analysis (ICA), has been used to exploit statistical correlations between electrodes, particularly in high density arrays, to decompose the P300 into separate components – i.e. to address the neural cocktail party problem [16]. Debener et al. [17] used ICA to identify the single-trial amplitudes of the error-related negativity (ERN), and correlated these with the BOLD response. They found activity in the rostral cingulate zone, an area thought to be involved in error-related processing. Though such correlations between the ERN and BOLD activity in the anterior cingulate (ACC) are interesting in their own right, it should be noted that the single-trial amplitudes they extracted were also correlated with reaction time (positively for the current trial and negatively for the subsequent trial) and thus the fMRI activation seen in the ACC could also potentially be explained by reaction time variability. In addition, and most importantly, the ICA method requires visual inspection and can thus introduce substantial bias when choosing components.

Our group has overcome most of the technical difficulties outlined above and has been able to develop a truly simultaneous EEG and fMRI recording system [18], [19], [20], [21], [22], which includes novel signal processing for artifact removal [23] and a discriminant based multivariate analysis framework for integrating single-trial variability of EEG with fMRI [24]. In my presentation I will outline our system and signal processing methodology for developing a new set of neuroimaging tools to more clearly delineate cortical networks imaged simultaneously with EEG and fMRI. Our system and signal processing framework enables the construction of EEG-derived fMRI activation maps which are not based on pre-defined labels or observed behavioral responses but rather on task and subject specific electrophysiological variability.

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