Abstract

Oscillatory activity in the brain has been associated with a wide variety of cognitive processes including decision making, feedback processing, and working memory control. The high temporal resolution provided by electroencephalography (EEG) enables the study of variation of oscillatory power and coupling across time. Various forms of neural synchrony across frequency bands have been suggested as the mechanism underlying neural binding. Recently, a considerable amount of work has focused on phase-amplitude coupling (PAC)– a form of cross-frequency coupling where the amplitude of a high-frequency signal is modulated by the phase of low-frequency oscillations.

The existing methods for assessing PAC have certain limitations which can influence the final PAC estimates and the subsequent neuroscientific findings. These limitations include low-frequency resolution, narrowband assumption, and inherent requirement of bandpass filtering. These methods are also limited to quantifying univariate PAC and cannot capture inter-areal cross-frequency coupling between different brain regions. Given the availability of multi-channel recordings, a multivariate analysis of phase-amplitude coupling is needed to accurately quantify the coupling across multiple frequencies and brain regions. Moreover, the existing PAC measures are usually stationary in nature, focusing on phase-amplitude modulations within a particular time window or over arbitrary sliding short time windows. Therefore, there is a need for computationally efficient measures that can quantify PAC with a high-frequency resolution, track the variation of PAC with time, both in bivariate and multivariate settings and provide a better insight into the spatially distributed dynamic brain networks across different frequency bands.

In this thesis, we introduce a PAC computation technique that aims to overcome some of these drawbacks and extend it to multi-channel settings for quantifying dynamic cross-frequency coupling in the brain. The main contributions of the thesis are threefold. First, we present a novel time-frequency based PAC (t-f PAC) measure based on a high-resolution complex time-frequency distribution, known as the Reduced Interference Distribution (RID)-Rihaczek. This t-f PAC measure overcomes the drawbacks associated with filtering by extracting instantaneous phase and amplitude components directly from the t-f distribution and thus provides high resolution PAC estimates. Following the introduction of a complex time-frequency-based high resolution PAC measure, we extend this measure to multi-channel settings to quantify the inter-areal PAC across multiple frequency bands and
brain regions. We propose a tensor-based representation of multi-channel PAC based on Higher Order Robust PCA (HoRPCA). The proposed method can identify the significantly coupled brain regions along with the frequency bands that are involved in the observed couplings while accurately discarding the non-significant or spurious couplings. Finally, we introduce a matching pursuit based dynamic PAC (MP-dPAC) measure that allows us to compute PAC from time and frequency localized atoms that best describe the signal and thus capture the temporal variation of PAC using a data-driven approach. We evaluate the performance of the proposed methods on both synthesized and real EEG data collected during a cognitive control-related error processing study. Based on our results, we posit that the proposed multivariate and dynamic PAC measures provide a better insight into understanding the spatial, spectral, and temporal dynamics of cross-frequency phase-amplitude coupling in the brain.

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