

Real-Time Estimation of Instantaneous Phase Synchrony: Tracking Global Coherence Brain Patterns and Physiological Arousal

L. Cóngyǔ¹, V. Taschereau-Dumouchel^{2 3}, A. Barosan^{4 5}, S. Van Gaal^{4 5}, J.D. Sitt¹

1 Institut du Cerveau - Paris Brain Institute - ICM, Inserm, CNRS, Sorbonne Université, Paris, France

2 Department of Psychology, Université de Montréal, Montreal, QC, Canada

3 Centre de Recherche de l'Institut Universitaire en Santé Mentale de Montréal, Montreal, QC, Canada

4 Department of Psychology, University of Amsterdam, Amsterdam, Netherland

5 Amsterdam Brain & Cognition, University of Amsterdam, Amsterdam, Netherland

Introduction

Current real-time functional magnetic resonance imaging (fMRI) network neurofeedback largely relies on sliding-window Pearson correlations (Monti et al., 2017; Long et al., 2021). However, sliding-window approaches are limited by their poor responsiveness to sudden network changes and the trade-off between temporal resolution and the statistical significance of observed functional connectivity fluctuations. As an alternative, Instantaneous Phase Synchrony (IPS) provides a measure of dynamic functional connectivity at a single-TR resolution, allowing researchers to extract instantaneous Coherence Brain Patterns (iCBPs). By analyzing the phase of the BOLD signals, iCBPs have been established as robust markers of cognition and consciousness.

Crucially, IPS has emerged as a robust marker for higher-order cognition and clinical application. It has been found that conscious brains dynamically explore a rich repertoire of configurations, alternating between a “High” pattern, characterized by robust long-range coherence across networks, and a “Low” pattern, characterized by sparse, local communication; while unconscious states only predominantly exhibit the “Low” pattern (Barttfeld et al., 2015; Demertzi et al., 2019). Furthermore, task fMRI experiment has indicated that whole-brain patterns exhibit greater synchronization during movie watching than during resting-state sessions (Türker et al., 2023).

Moving beyond localized connectivity paradigms, this project aims to advance towards a closed-loop real-time fMRI approach targeting global iCBP architecture, which holds therapeutic potential for Disorders of Consciousness. Therefore, this study evaluates the feasibility and accuracy of an online IPS computation pipeline to track these global states in real-time. We expand the analysis to validate these network dynamics in the context of physiological arousal measured by pupil size.

Methods

The study utilized task fMRI recordings from 16 participants. Each participant's data consisted of 4 runs and 398 TRs per run. To establish a baseline, the offline data underwent standard preprocessing, including slice-timing correction, magnetic field distortion correction, motion correction, spatial registration and denoising. Timeseries were extracted from 42 regions of interest (ROIs) aligned to MNI space and bandpass-filtered between 0.008 and 0.09 Hz. After a Hilbert transform, pairwise IPS was subsequently computed. Then we applied K-means clustering to gain 3 cluster centroids, as well as assigned the functional connectivity of each timepoint to them. This offline pipeline is aligned with the one used in previous studies for iCBP (Demertzi et al., 2019; Türker et al., 2023).

To simulate real-time processing, the MNI-space ROIs were mapped to native space using subject-specific structural scans. Real-time preprocessing and ROI timeseries extraction were handled sequentially using OpenNFT (Koush et al., 2017). The resulting Kalman-filtered timeseries were bandpass-filtered between 0.008 to 0.09 Hz. To mitigate the edge effects inherent in Hilbert transform and enable immediate IPS computation, Autoregressive (AR) Padding was utilized to forecast future data points. Incoming iCBPs that passed the confidence gating threshold were assigned to the baseline K-means centroids. The AR Padding parameters and the confidence gating threshold were calculated during a baseline run.

Furthermore, concurrent pupil size data were extracted and preprocessed to provide a physiological validation of the dynamic network states, mapping onto the “High” and “Low” patterns.

The performance of the online AR-Kalman pipeline was evaluated against the offline ground truth through multiple metrics such as correlation accuracy of the timeseries, Spatial similarity between the continuous IPS as well as the averaged iCBPs, and accuracy of the state label assignments.

Results

Although the timeseries and IPS series show low correlation between the online and offline methods, discrete state assignment accuracy of the online clustering remained significantly above the theoretical chance level. Among the three defined iCBPs centroids, the pattern associated with small pupil sizes exhibited lower detection accuracy compared to the pattern associated with large pupil sizes. The pupil size effect was also partially replicated with the online process. While the spatial configurations of the averaged brain patterns were preserved in the online data, the overall state occupancy distributions were not fully reproduced. A substantial drop was observed in the occurrence rate of the state corresponding to small pupil sizes with the online pipeline.

To diagnose the problem, a Kalman-filter-only approach to an AR-padding-only approach were conducted. While both isolated methods yielded similar levels of continuous timeseries and IPS correlation, the Kalman-filter-only approach demonstrated worse performance in discrete state labeling and occupancy replication, most notably with the pattern associated with large pupil sizes.

Furthermore, individual differences were observed: both the optimal AR padding parameters and the baseline iCBPs topographies varied significantly across participants, highlighting the necessity for subject-specific parameter optimization.

Conclusions

The implementation of an online pipeline utilizing a Kalman-filter and AR-padding demonstrates the feasibility of tracking global iCBPs in real-time. By classifying whole-brain network states at an accuracy significantly above chance and replicating the pupil size effect observed in the offline data, this method offers a potential alternative to localized sliding-window approaches for fMRI functional connectivity neurofeedback in consciousness studies.

However, limitations were observed in the pipeline's ability to detect certain patterns. Diagnostic analyses indicate that this issue likely originates in the preprocessing stage. We propose that the Kalman-filter may introduce excessive temporal smoothing, thereby obscuring short-duration effects that require high temporal resolution to accurately detect. Furthermore, the variance observed in optimal AR parameters and baseline iCBPs topographies highlights the importance of addressing individual differences. Future studies should focus on developing individualized pipelines, alongside optimized preprocessing and clustering methods, to achieve higher accuracy in continuous IPS prediction.

References (optional, maximum 6)

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