A Time-Frequency Based Bivariate Synchrony Measure for Reducing Volume Conduction Effects in EEG

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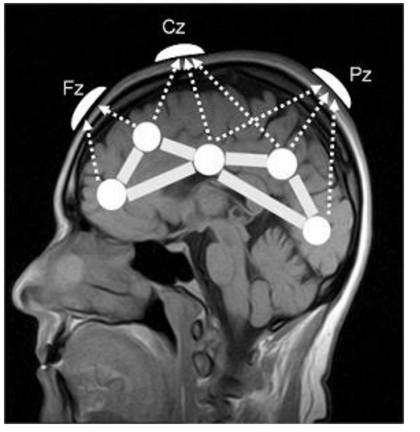
Motivation

- Functional connectivity (FC) is defined as the statistical dependence among two or more brain regions (Friston, 1994).

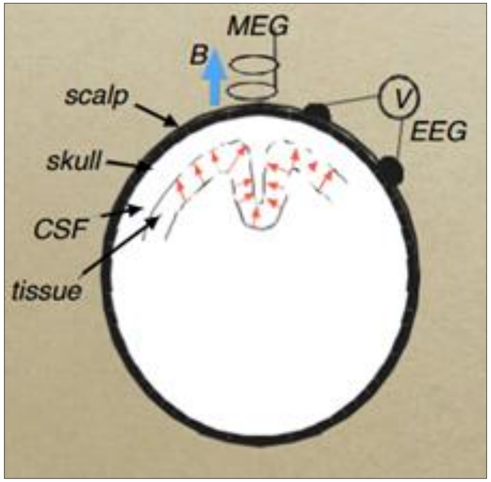


http://psychophysiology.blogspot.com/2007_11_01_archive.html

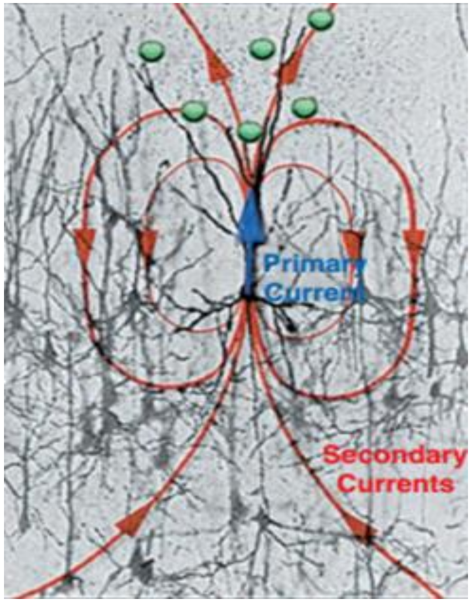
- Problem:
  - Volume conduction affects FC measures from electrophysiological techniques.
  - Each sensor records the instantaneous linear superposition of multiple brain sources (Khadem and Hossein-Zadeh, 2014).
  - May lead to spurious detection of functional connections among channels.

Neuronal Origin of Electromagnetic Brain Signals

- **Electromagnetic fields measured in the scalp result from coordinated cortical activity.**
  - Electroencephalography (EEG): electric fields.
  - Magnetoencephalography (MEG): magnetic fields.



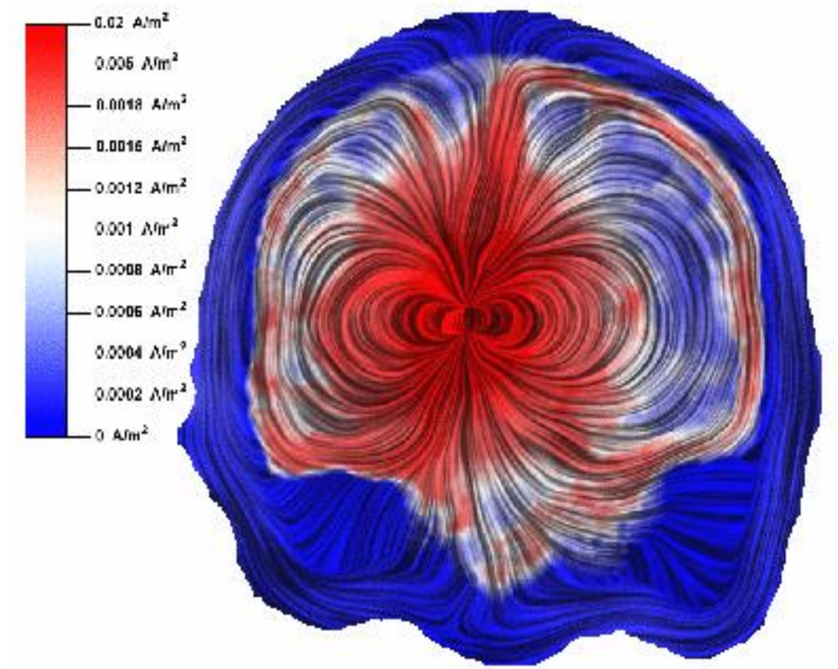
http://www.isr.umd.edu/Labs/CSSL/simonlab/pubs/APAN2010.pdf



From Baillet et al., 2001

Volume Conduction

- Due to conductivity of the medium, electrical currents spread through different layers.
- Skull has high resistance: electrical signals spread laterally.



Volume currents for a thalamic dipole source (from Wolters et al. , 2006).

Volume Conduction Reduction Approaches

- Source reconstruction: FC is based on brain sources reconstructed from scalp measurements.
  - No unique choice for a source model.
  - Total number of sources is unknown.

- Spatial filtering prior to the computation of functional connectivity.

- FC directly estimated from phase-lag methods.
  - Imaginary part of coherence (Nolte et al., 2004)
  - Phase lag index (PLI) (Stam et al., 2007)
  - Weighted phase lag index (WPLI) (Vinck et al., 2011)

Imaginary Part of Coherency (Nolte et al. 2004)

- Coherency:

$$C_{ij}(f) = \frac{S_{ij}(f)}{\sqrt{S_{ii}(f)S_{jj}(f)}}, \text{ where } S_{ij}(f) = < x_i(f), x_j^*(f) >.$$

- Only the real part of coherency is affected by volume conduction.
  - Assume that signals at sensors i and j result from the linear combination of K sources.

$$x_i(f) = \sum_{k=1}^{K} a_{ik} s_k(f) \quad x_j(f) = \sum_{k=1}^{K} a_{ik} s_k(f)$$

  - Then,

$$S_{ij}(f) = < x_i(f), x_j^*(f) > = \sum_k a_{ik} a_{jk} < s_k(f), s_k^*(f) > = \sum_k a_{ik} a_{jk} |s_k(f)|^2$$

Phase-Lag Index (Stam et al. 2007)

- Measure of the asymmetry on the distribution of phase differences.
  - Constant nonzero phase lags between two electrophysiological signals cannot result from volume conduction caused by a strong source.

$$PLI = |\langle sign[\Delta\Phi_k]\rangle|,$$

where $\Delta\Phi_k = \Phi_i - \Phi_j$.

- Problem: discontinuity of PLI due to small perturbations which turn phase lags into leads and vice-versa.

Weighted Phase Lag Index (Vinck et al., 2011)

- Observed phase leads and lags are weighted by the magnitude of the imaginary component of the cross-spectrum.
  - Reduced sensitivity to uncorrelated noise sources
  - Increased statistical power to detect changes in phase synchronization.

$$WPLI = \frac{\left|E\left[Im(S_{ij})\right]\right|}{E\left[\left|Im(S_{ij})\right|\right]}$$

- WPLI does not separate the effects of amplitude and phase between two signals.
  - Modify WPLI as

$$WPLI(t,\omega) = \frac{\left|\left\langle \sin\left(\Phi_{1,2}^{k}(t,\omega)\right)\right\rangle\right|}{\left\langle\left|\sin\left(\Phi_{1,2}^{k}(t,\omega)\right)\right|\right\rangle},$$ where $\langle\cdot\rangle$ denotes averaging over trials.

Reduced Interference Distribution (RID) Rihaczek time-frequency distribution

- For a signal x_i, define $C_i(t,\omega)$ to be its complex RID-Rihaczek time-frequency distribution

$$C_i(t,\omega) = \iint exp\left(-\frac{(\theta\tau)^2}{\sigma}\right) exp\left(j\frac{\theta\tau}{\sigma}\right) A_i(\theta,\tau) e^{-j(\theta t+\tau\omega)} d\tau d\theta,$$

where $A_i(\theta,\tau)$ is the ambiguity function of x_i:

$$A_i(\theta,\tau) = \int x_i\left(u+\frac{\tau}{2}\right) x_i^*\left(u-\frac{\tau}{2}\right) e^{j\theta u} du.$$

- The time-varying phase of x_i is given as

$$\Phi_i(t,\omega) = arg\left[\frac{C_i(t,\omega)}{|C_i(t,\omega)|}\right].$$

- The phase difference between two signals x_1 and x_2 is computed similarly as

$$\Phi_{1,2}(t,\omega) = arg\left[\frac{C_1(t,\omega)}{|C_1(t,\omega)|}\frac{C_2^*(t,\omega)}{|C_2(t,\omega)|}\right].$$

Continuous Wavelet Transform (CWT)

- For a signal x_i, define $W_i(t,\omega)$ to be its CWT given by

$$W_i(t,\omega) = \int_{-\infty}^{\infty} x(u)\Psi_{t,f}^{*}(u)du$$

$$\Psi_{t,f}(u) = \sqrt{f}e^{j2\pi f(u-t)}e^{-\frac{(u-t)^2}{2\sigma^2}}$$

where $\Psi_{t,f}(u)$ corresponds to a Gaussian window centered at time t with variance σ^2 modulated by a complex exponential at frequency f.

- The time-varying phase of the signal x_i is computed as

$$\Phi_i(t,\omega) = arg\left[\frac{W_i(t,\omega)}{|W_i(t,\omega)|}\right].$$

- The phase difference between two signals x_1 and x_2 is computed similarly as

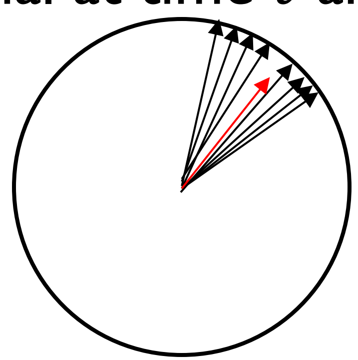
$$\Phi_{1,2}(t,\omega) = arg\left[\frac{W_1(t,\omega)}{|W_1(t,\omega)|}\frac{W_2^{*}(t,\omega)}{|W_2(t,\omega)|}\right].$$

Phase-Locking Value (PLV)

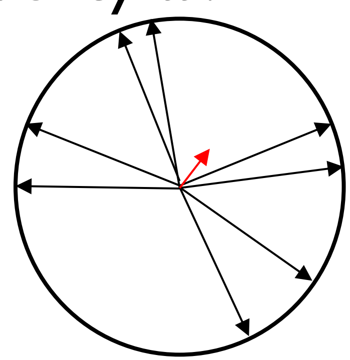
- For two signals x_1 and x_2 the PLV is defined as

$$PLV_{1,2}(t,\omega) = \frac{1}{N}\left|\sum_{k=1}^{N} \exp\left(j\Phi_{1,2}^{k}(t,\omega)\right)\right|$$

where N corresponds to the total number of trials in the experiment and $\Phi_{1,2}^{k}$ is the phase difference between x_1 and x_2 for the k^{th} trial at time t and frequency ω.



High PLV

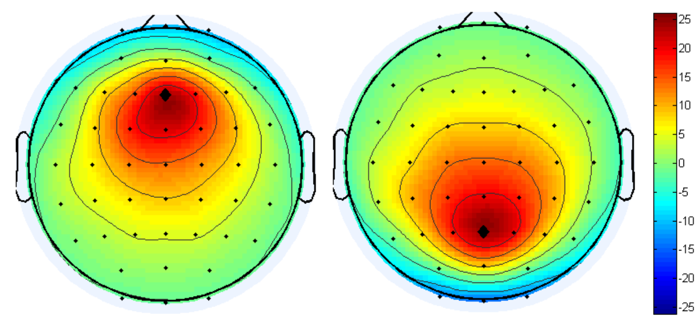


Low PLV

Simulated EEG Data

- Based on the model provided by Cohen (2014):
  - 2004 spatially distributed gray matter dipoles, simulated by Gaussian random variables, $\mu = 0, \sigma^2 = 0.6 \times 10^{-3}$.
  - 100 trials, Fs = 200 Hz

- Two active dipoles modeled as Gaussian tapered sine waves in additive noise:
  - medial prefrontal cortex (PFC)
  - medial occipital cortex (OCC)

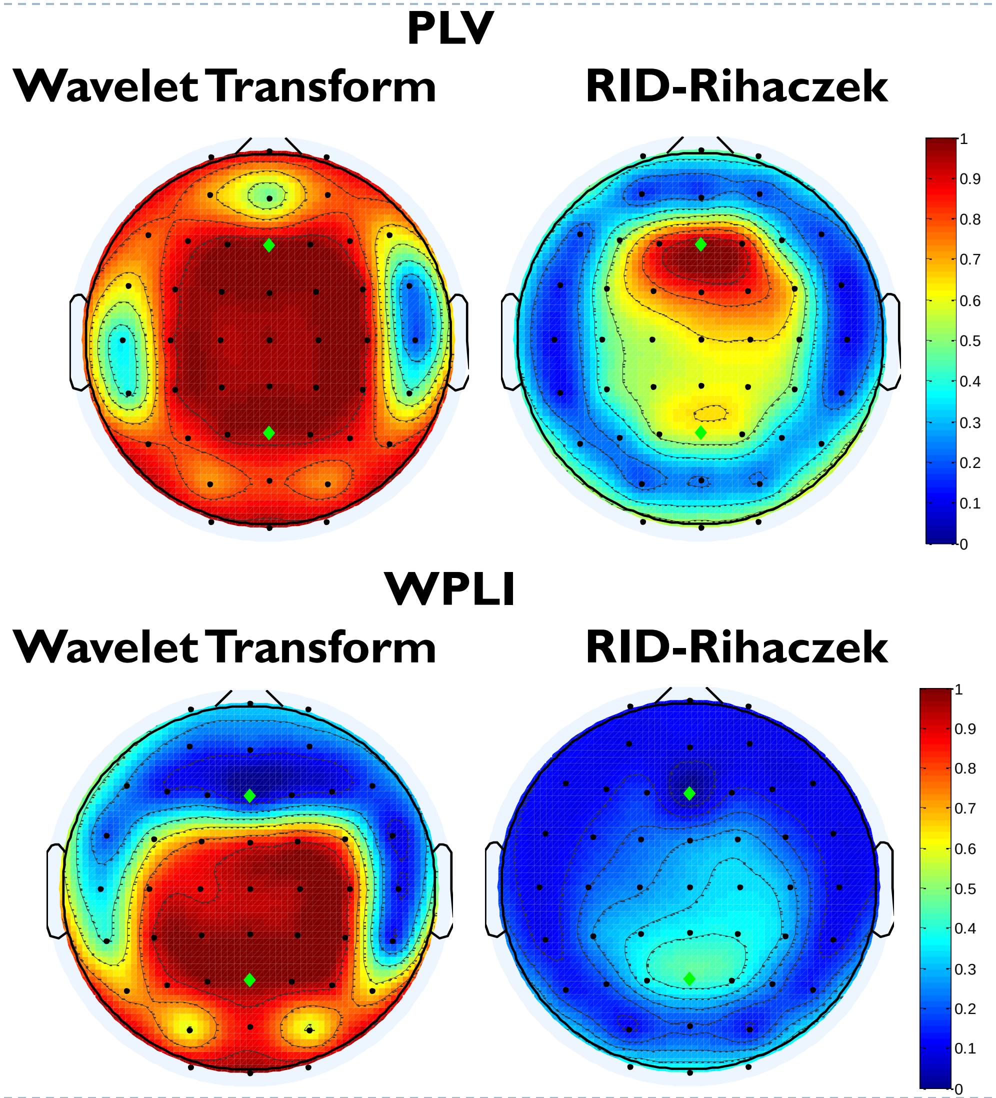


$$x_{PFC}(t) = \eta_{PFC}(t) + \sin(2\pi 10t + \emptyset_1(t)) \times e^{\frac{-(t-0.6)^2}{0.1}}$$

$$x_{OCC}(t) = \eta_{OCC}(t) + [\eta_{PFC}(t) + \sin\left(2\pi 10t + \emptyset_2(t)\right) \times e^{\frac{-(t-0.6)^2}{0.1}}] \times e^{\frac{-(t-0.6)^2}{0.1}}$$

Results: EEG Simulated Data

- PLV and WPLI computed between Fz and the remaining 63 electrodes.
- Averaged over 9-11 Hz and 300-900 ms.
- Expected high synchrony between Fz and Pz.
- PLV: Both methods identify high synchrony between Fz and nearby electrodes.



EEG Data

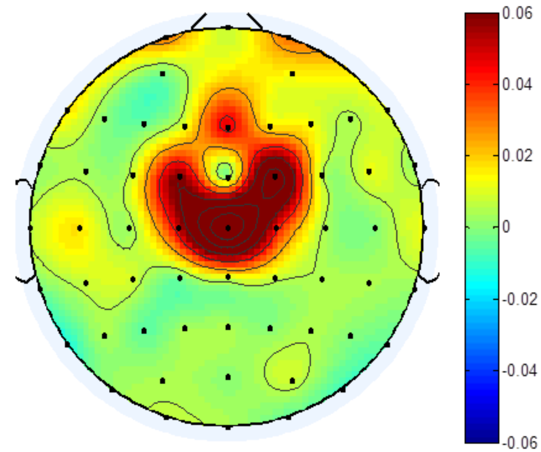
- EEG data from a cognitive control-related error monitoring experiment.
  - Error-related negativity (ERN) potential: 25 – 75 ms after errors in a speeded reaction time tasks.
  - Linked to increased synchronization in the theta-band (4-8 Hz), in central and frontal regions compared to central and parietal regions (Cavanagh et. al., 2009).

- Experiment:
  - Letter version of the Eriksen flanker task.
  - Identify a target (central) letter in a five-letter string: NNMNN
  - 19 subjects.
  - EEG signals recorded from 62 electrodes according to the 10/20 system.

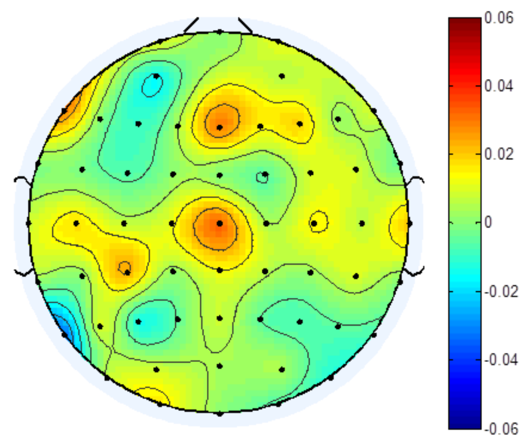
Results: EEG Data

- Topographical plots for error-correct synchrony (RID-Rihaczek) differences.
- Electrode FCz as reference.
- PLV detects high synchrony between the medial frontal and medial central regions.
- WPLI synchrony results in moderately high synchrony between FCz and the medial frontal and central electrodes.
  - Synchrony is not strictly due to volume conduction or small phase differences.

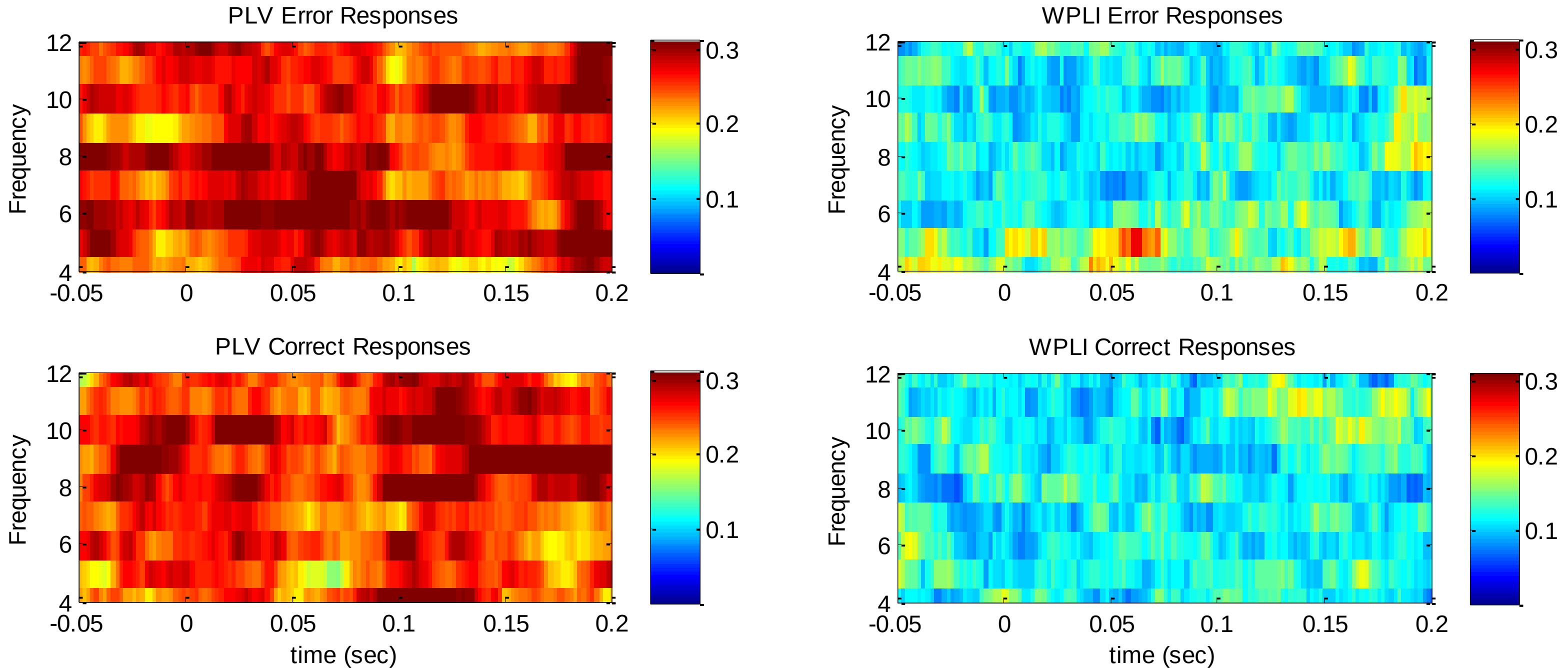
PLV



WPLI



Results: EEG Data



- Time-frequency synchrony maps between FCz and Fz electrodes.
- Low synchrony from WPLI for correct responses:
  - High synchrony from PLV might be due to the influence of volume conduction.
- High WPLI synchrony is concentrated in the low theta band during the ERN interval.
  - Phase synchrony in the frontal-central region during error is not purely due to volume conduction.

Conclusions and Future Work

- A WPLI based on the RID-Rihaczek time-frequency distribution has been presented and compared to the WPLI based on the CWT.
  - Robust to volume conduction.
  - Better localized synchrony.

- As suggested by (Cohen 2014), in the case of real EEG data there are multiple factors in addition to volume conduction:
  - Noise
  - Non-stationarities
  - Small phase lags

Questions?