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Phase Synchrony Neurofeedback? BEWARE!

Background

Phase synchrony estimation in EEG signals is subject to a number of pitfalls, which makes neurofeedback protocols rare, despite their potential in health care applications (epilepsy syndromes, attention deficit hyperactivity disorder.).

Phase synchrony measures the consistency of a relationship between the phase of two signals. It requires in the first phase the determination of a phase (or phase difference), and in the second phase the quantification of this consistency.

EEG signals are the combination at the scalp of the activity of the neurons of the cortex, plus possibly external noises.

A simple, if likely generic assumption (especially in the framework of phase synchrony), is to assimilate EEG signals to locally stationary weighted sums of sinusoids:

\[ f(t) = \cos(\omega t + \phi(t)) \]

Methodology

A) From the fundamentally equivalent methods to extract the phase from EEG signals, we retained the Morlet Wavelet Transform. We derive analytically a convolution of a Morlet wavelet with a sinusoid and extend the derivation to the weighted sums of locally stationary sinusoids. Additionally, we propose an approximation of the former derivation with loose constraints.

The behavior of the weights for varying width and frequencies is analyzed.

We present two cases of false synchrony: one of missed synchrony, and one of spurious synchrony.

B) The correlation coefficients of two 6ft distant Morlet wavelet coefficients is computed.

C) We set up an experiment to assess the correlation between common phase synchrony measures. A subject underwent 13 recordings of 275 seconds, alternating between 20s of Eyes Open Fixation of the screen (Baselines) and 20s of Eyes Closed Relaxation. Interleaving 5 seconds of rest between each event.

Results

A) The wavelet transform is an accurate estimation of the argument of a sine wave for Q > 2. The benefit of increasing the width of the wavelet (Q) to values higher than 30 is minimal, and at the expense of reducing the temporal accuracy of the transform.

The higher the frequency of interest (\( \nu_s \)) is, the more mixing between frequency components (\( \nu_s \)) around that frequency (respecting the uncertainty principle).

The amplitude ratio between components matters in the phase estimation, but tightly in comparison to the distance ratio between \( \nu_s \) and \( \nu_n \).

This phase between two pairs of sinusoids oscillating in the vicinity of the wavelet frequency (\( \nu_s \)) is almost zero for two different pairs of sinusoids (i.e. \( \nu_w = 9.5, \nu_s = 11; \nu_w = 10, \nu_s = 11 \)).

It means that the phase is not unique: several combinations of different frequencies produce the same phase.

B) The derivation of the correlation between two close coefficients show that they are not independent.

C) Some synchrony measures are strongly correlated and thus redundant: PLI and ImCh or PLV and Cach are strongly correlated, on the other hand PLI and PLV are complementary, and would benefit from being analyzed altogether when assessing synchrony.

Conclusion

Assessing properly phase synchrony is a real challenge, even for offline analysis. It has mostly to do with the volume conduction / volume leakage mixing, the uncertainty principle and the redundancy of the wavelet coefficients.

One or more of these issues are often neglected. We provide a framework for better understanding and interpreting phase extraction with the Morlet Wavelet Transform to show that errors are made when extracting phase information and must be accounted for.

Before attempting to blindly use phase synchrony measures in Neurofeedback, there a fortiori a need for a proper and efficient estimation of the statistical significance of the measures calculated on the fly.

Wavelet Transform:

\[
WT(f(t))(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} f(t) \exp(-itk) dt
\]

\[
\text{For } f(t) = \exp(it\phi) \text{ the argument } \arg(f(t)) = \phi(t).
\]

\[
\phi(t) = \text{arctan}(\text{Im}(f(t))/\text{Re}(f(t)))
\]

\[
\frac{\text{Im}(f(t))}{\text{Re}(f(t))} = \frac{\sin(\text{arg}(f(t)))}{\cos(\text{arg}(f(t)))}
\]

\[
\text{arg}(f(t)) = \tan^{-1}(\text{Im}(f(t))/\text{Re}(f(t)))
\]

The phase difference between two different combinations of sinusoids oscillating at different frequencies can be constant (\( \nu_w = 9.5, \nu_s = 11 \)). It means the perfect synchrony can be completely spurious.

It’s invaluable in such case, since it requires a symmetry with respect to the wavelet frequency, and be close enough in the width of the wavelet.

\[
\rho(WT(k), WT(k + \delta_k)) = \sum_{k} W(t)W(t - \delta_k)
\]

Under the hypothesis of an EEG signal modeled as sequence of random variables with same means and same variance, we show that close coefficients are correlated. Hence, wavelet coefficients’ independence should not be assumed in statistical tests. Their correlation equals the auto-correlation of the wavelet and thus, depends on the width (and available parts).

This correlation coefficient can be used to sub-sample the wavelet coefficients in order to minimize their correlation. In turn, this coefficient must be introduced in statistical significance testing.

Phase synchrony is restored for a wavelet at 10Hz. The formula shows clearly why one sees on the jumps occur at the frequency of the signal.

The effect on the phase of varying the frequency ratio (signal vs wavelet) up to high values:

- Some measures are redundant: PLI and ImCh or PLV and Cach are strongly correlated, on the other hand PLI and PLV are complementary, and would benefit from being analyzed altogether when assessing synchrony.

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Baseline

For instance, strong PLV and PLI values occurring during eyes closed can be a measure of a strong synchrony between electrodes of a given pair.