Cross-frequency
power-power coupling analysis toolbox
(PowPowCAT)

Makoto Miyakoshi
Advanced Topics in The 30th EEGLAB workshop
Nov 30, 2021 11:00-11:45 pm
What’s the difference?

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Power (10*log10 μV²/Hz)</th>
<th>Frequency (Hz)</th>
<th>Power (10*log10 μV²/Hz)</th>
</tr>
</thead>
</table>

[Graphs showing power spectral density]
How about this?

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Power (10*log10 μV²/Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10 Hz</td>
</tr>
<tr>
<td>20</td>
<td>20 Hz</td>
</tr>
<tr>
<td>50 or 60</td>
<td>50 or 60 Hz</td>
</tr>
</tbody>
</table>

Power (10*log10 μV²/Hz) vs Frequency (Hz)
What is harmonics?

Wikipedia ‘harmonics’

Wikipedia ‘square wave’
Virtual John Iversen’s explanation

- **Fundamental**
- **1st harmonics**
- **2nd harmonics**
- **3rd harmonics**

**Frequency (Hz)**

**Power (10*log10 μV²/Hz)**
Double peaks does not guarantee cross-frequency coupling

Thammasan and Miyakoshi (2020)
Why do I like power-power coupling?
List of cross-frequency relations 1

Jirsa and Müller (2013)
List of cross-frequency relations 2

Jirsa and Müller (2013)
Reasons to analyze EEG power rather than phase

• Phase is a noisy metric, has weird dependency on amplitude contrary to the intuition, etc.
• Power metric has good biological evidence: population coding.
• ‘PowPowCAT’ is a good name which I must publish.
Why is harmonics important in EEG?

Power Spectral Density of averaged Steady-State Visual Evoked Potential (SSVEP) at Oz, O1, O2.

Regional cerebral blood flow (rCBF) measured with $\text{H}_2^{15}\text{O}$ PET. Red, fundamental freq-weighted. Blue, first harmonics-weighted.

Pastor et al. (2006)
Why is harmonics important in EEG? 2

On- and off-neuron responses recorded from cat lateral geniculate nucleus (LGN) during visual stimulation.

Podvigin et al. (2004)
How to calculate power-power coupling
Comodulogram as spectral covariance

When $X$ is the time-frequency decomposed power with length $k$,,

$\text{Comodulogram}(X) = \text{mean}_{\text{time}} \times \begin{pmatrix} \text{z-scored}_{\text{time}} \text{ ERP} \\ \text{z-scored}_{\text{time}} \text{ ERP} \end{pmatrix}$
Demonstration of PowPowCAT
‘stern_125.set’ (tutorial dataset) IC scalp topos
‘stern_125.set’ Comodulogram
IC6 vs. IC8—What’s the best description of the difference?
IC6 shows a nice second harmonics ($r=0.356$)
4TH harmonics captured!
How a muscle IC is nicely represented

Thammasan and Miyakoshi (2020)
Comodulogram helps classify the ICs

Even if the class probability is low, comodulogram can detect true signature of the brain signal!
Comodulogram for IC classification

‘The diagonal line of comodulogram is the power spectral density (PSD). When used in machine learning, comodulogram could be more informative than PSD.’

Thammasan and Miyakoshi (2020)
Conclusion

• Cross-frequency power-power coupling plot is called comodulogram.
• Comodulogram is an extension of power spectral density (PSD) which tells us temporal correlations across time series of power fluctuations in different frequency bands.
• Comodulogram provides additional information about the independent components (ICs) that has been neglected but now proven to classify them.
• PowPowCAT has been available since 2017 to calculate the comodulogram.
  • Recently batch mode is supported upon request of Pål from Oslo.
Mini history of PowPowCAT

- The prototype of PowPowCAT was developed as ‘re-inventing the wheel’.
  In the final revision, PPC was ad hoc re-invented by MM to convince Michael that the 44-Hz peak in the PSD of his EEG data was not related to other brain signals.
- The original EEGLAB plugin was published on January 3, 2017.
- I continued to develop it during the 23rd EEGLAB workshop in January 2017 at Mysuru, India.
- Proposed to Nattapong from Osaka University as a ‘souvenir project’.
  - E-mail discussion with György, Daniel, Dion, and Brendon.
  - First submitted in 2017 (rejected).
  - The second submission accepted in 2020.

Nattapong Thammasan
Visiting scholar at SCCN
Jan-Mar 2017

Article
Cross-Frequency Power-Power Coupling Analysis: A Useful Cross-Frequency Measure to Classify ICA-Decomposed EEG
Nattapong Thammasan and Makoto Miyakoshi
Thank you for your attention

Artwork by Mayumi and Makoto Miyakoshi
A mini review of the power-power coupling analysis by Nattapong Thammasan (University of Twente)
Envelope-Envelope Coupling

Bekisz & Wróbel, 1999
*Neuroreport*
Cross-correlation between envelopes of filtered beta and gamma oscillatory signals

Jirsa & Müller, 2013
Review paper
Envelope-Envelope Coupling

Neuroreport
Amplitude-envelope correlation (AEC) of filtered signals
Bruns et al., 2000

Int. J. Psychophysiol
Correlation between corresponding envelope segments
Bruns & Eckhorn, 2004
Envelope-Envelope Coupling

Bekisz & Wróbel, 1999

Cross-correlation function between envelopes of beta and gamma signals

Bruns et al., 2000

Illustration of AEC method
Envelope-Envelope Coupling

Bruns & Eckhorn, 2004

Pronounced task-related increase of gamma-delta envelope-to-signal correlation between superior and inferior occipital visual area → possibly reflecting a short-term memory encoding process

Jirsa & Müller, 2013

\[
\rho_X^{(k)}(f_m, f_n, t) = \frac{\sum_{\tau\in\tau} a_{X^{(k)}}(\tau, f) \cdot a_{Y^{(k)}}(\tau, f)}{\sqrt{E_X^{(k)}(f_m, f_n, t) \cdot E_Y^{(k)}(f_m, f_n, t)}}
\]

Strongest in 5-14 Hz, Coupling in EC > in EO
Envelope-Envelope Coupling

- Bruns & Eckhorn, *Int. J. Psychophysiol*, 2004
  - correlation between corresponding envelope segments was determined after subtracting the segments' means and correlation values were normalized to segment energies:

\[
\rho_{XY,\lambda}(t,f) = \frac{\sum_{\tau \in I_t} a'_{X,\lambda}(\tau,f) \cdot a'_{Y,\lambda}(\tau,f)}{\sqrt{E'_{X,\lambda}(t,f) \cdot E'_{Y,\lambda}(t,f)}}
\]

where \( a'_{X,\lambda}(\tau,f) = a_{X,\lambda}(\tau,f) - \overline{a_{X,\lambda}(\tau,f)} \) (\( \tau \in I_t \)) denotes an envelope segment with its mean subtracted, and \( E'_{X,\lambda}(t,f) = \sum_{\tau \in I_t} a'_{X,\lambda}(\tau,f) \) is the energy of that segment. Finally, correlation values were averaged across trials, using Fisher’s Z transform \( FZT(\rho) = \tanh^{-1}(\rho) \):

\[
\rho_{XY}(t,f) = FZT^{-1}\left(\frac{1}{N} \sum_{\lambda=1}^{N} FZT(\rho_{XY,\lambda}(t,f))\right).
\]

[Correlation map image]