



MRC Cognition  
and Brain  
Sciences Unit



UNIVERSITY OF  
CAMBRIDGE

# **EEG/MEG 3:**

## **Functional Connectivity Analysis**

Olaf Hauk

[olaf.hauk@mrc-cbu.cam.ac.uk](mailto:olaf.hauk@mrc-cbu.cam.ac.uk)

# Brain Connectivity

## **Structural/Anatomical Connectivity:**

Hardware links between brain regions  
(e.g. DWI/DTI).

## **Functional Connectivity:**

Statistical dependencies of activation between brain regions  
(e.g. correlation, or spectral measures such as phase-locking and coherence).

## **Effective Connectivity:**

Causal interactions of activation between brain regions  
(Granger Causality, Dynamic Causal Modelling).

For example:

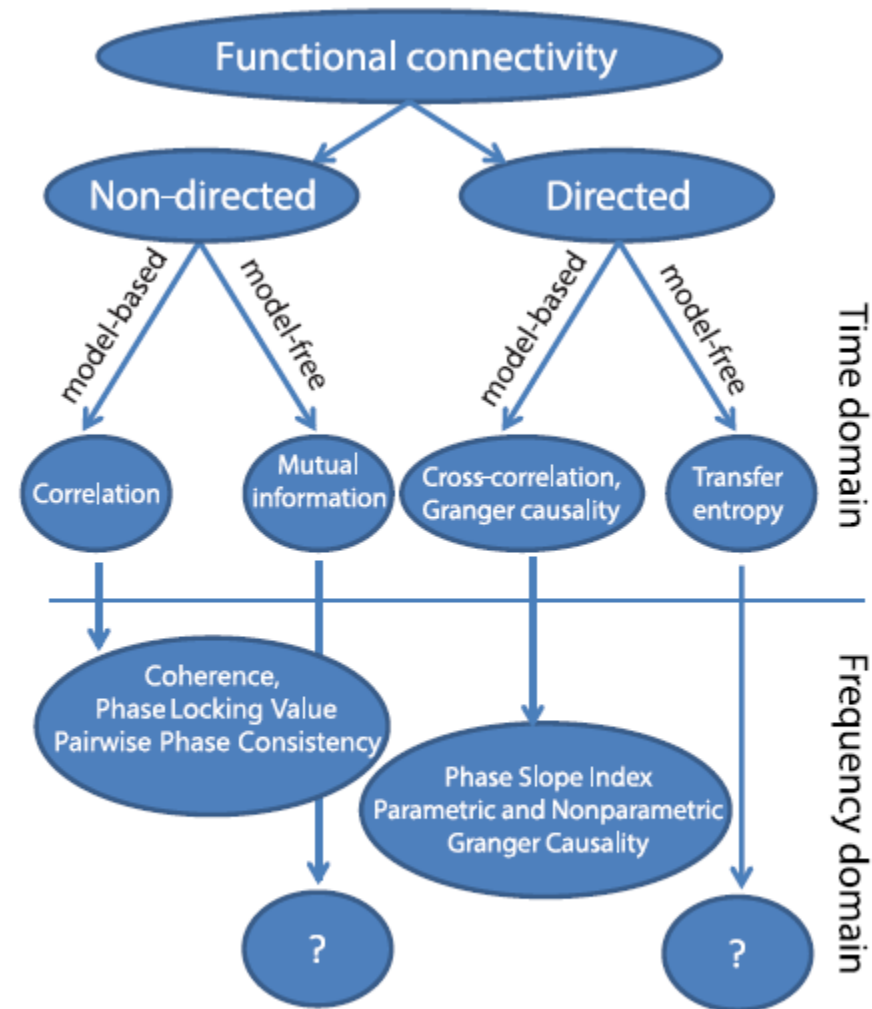
<http://journal.frontiersin.org/article/10.3389/fnsys.2015.00175/full>

<http://www.sciencedirect.com/science/article/pii/S0165027012000817>

<http://www.ncbi.nlm.nih.gov/pubmed/21477655>

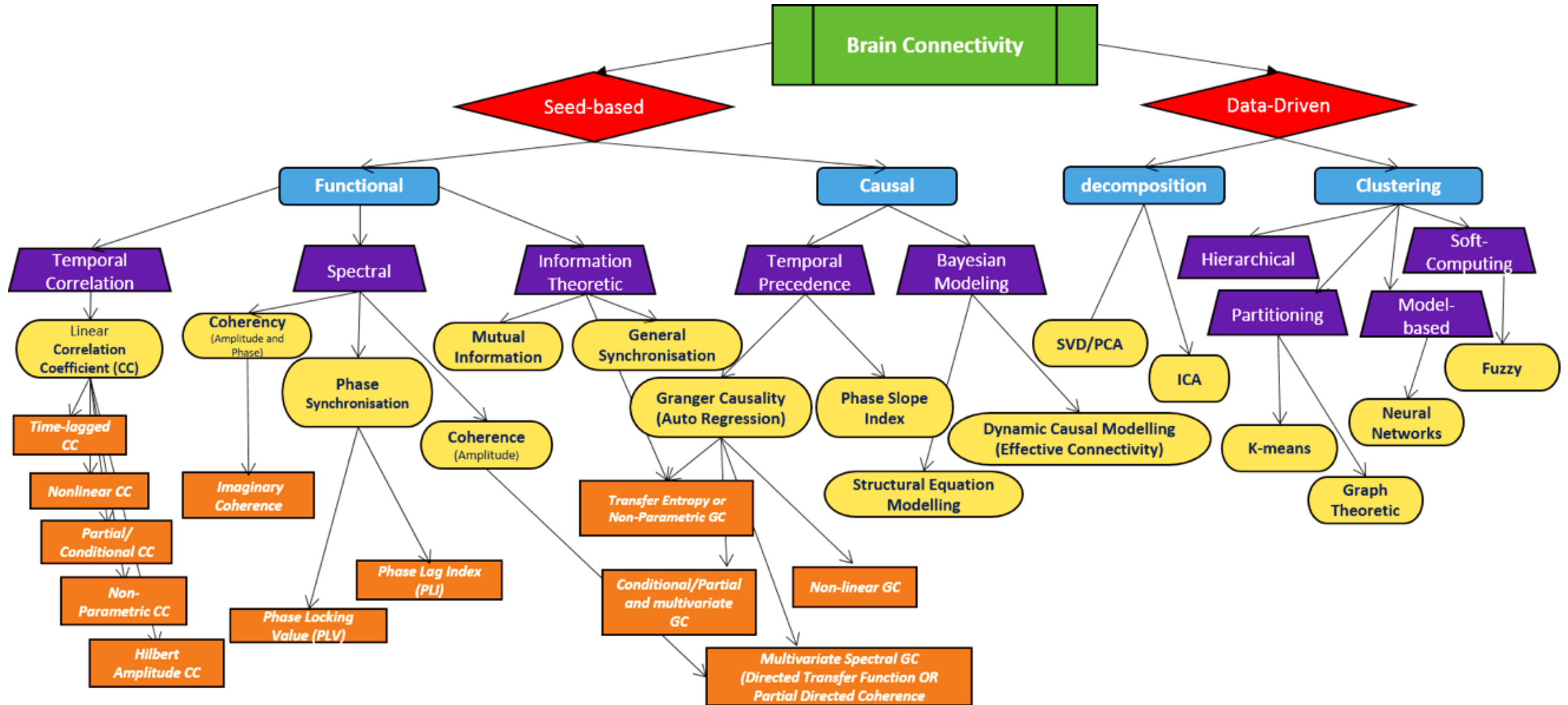
<http://online.liebertpub.com/doi/abs/10.1089/brain.2011.0008>

# Taxonomy Of Popular Functional Connectivity Methods



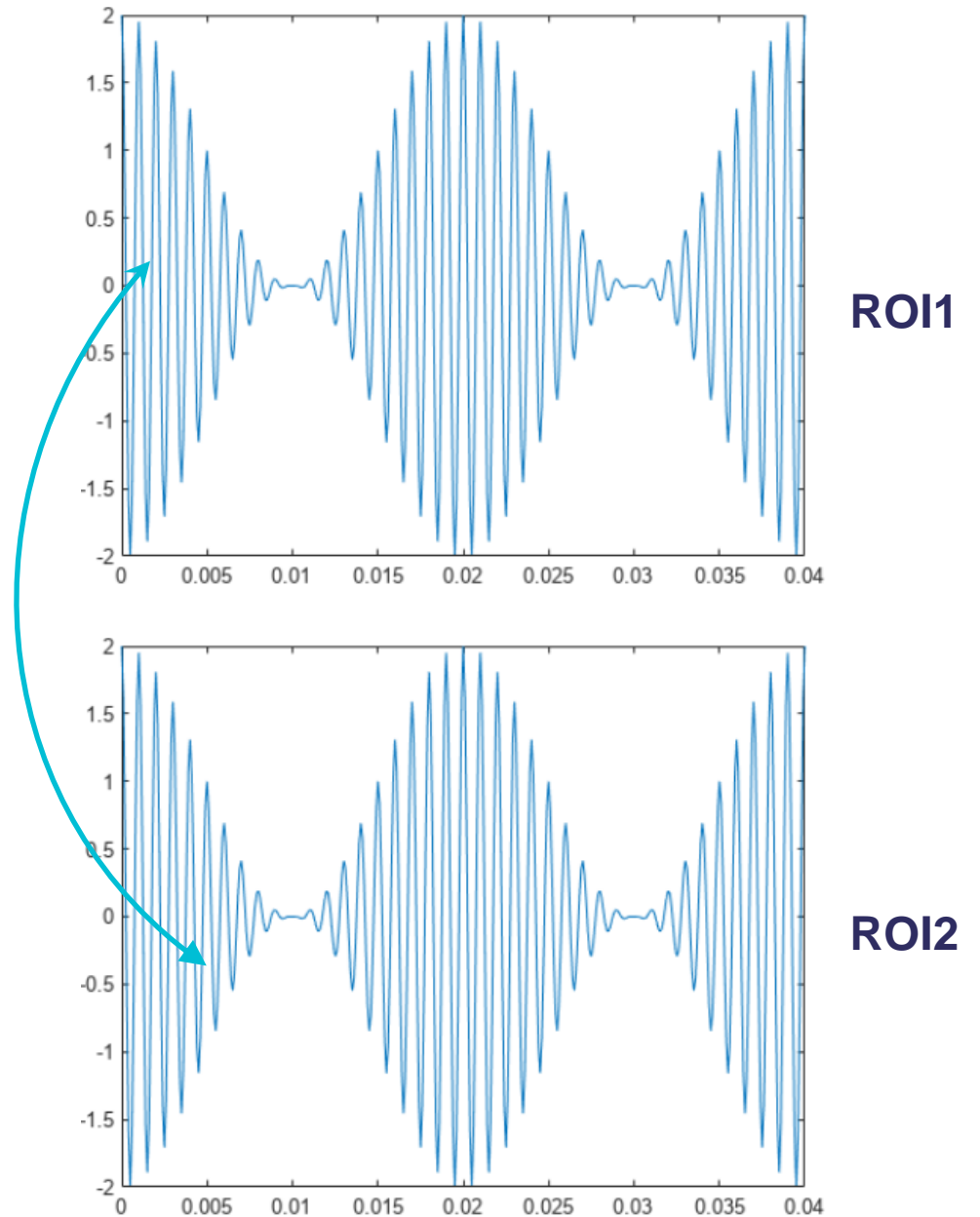
**FIGURE 1 | A taxonomy of popular methods for quantifying functional connectivity.**

# “Brain Connectivity”



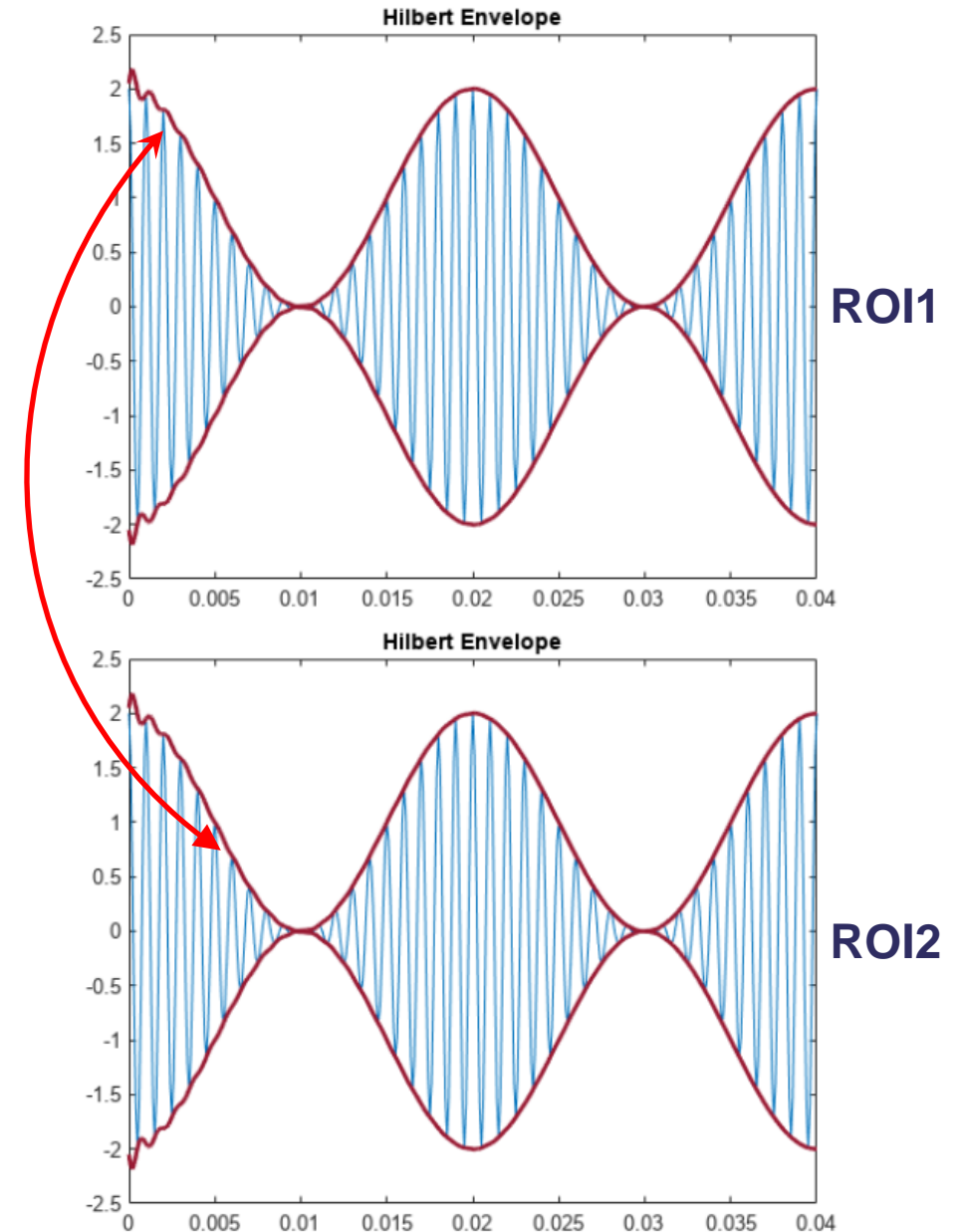
# Temporal Correlation of Timecourses

“Naïve” correlation of timecourses would be very susceptible to small disturbances in the data with respect to time and frequency.



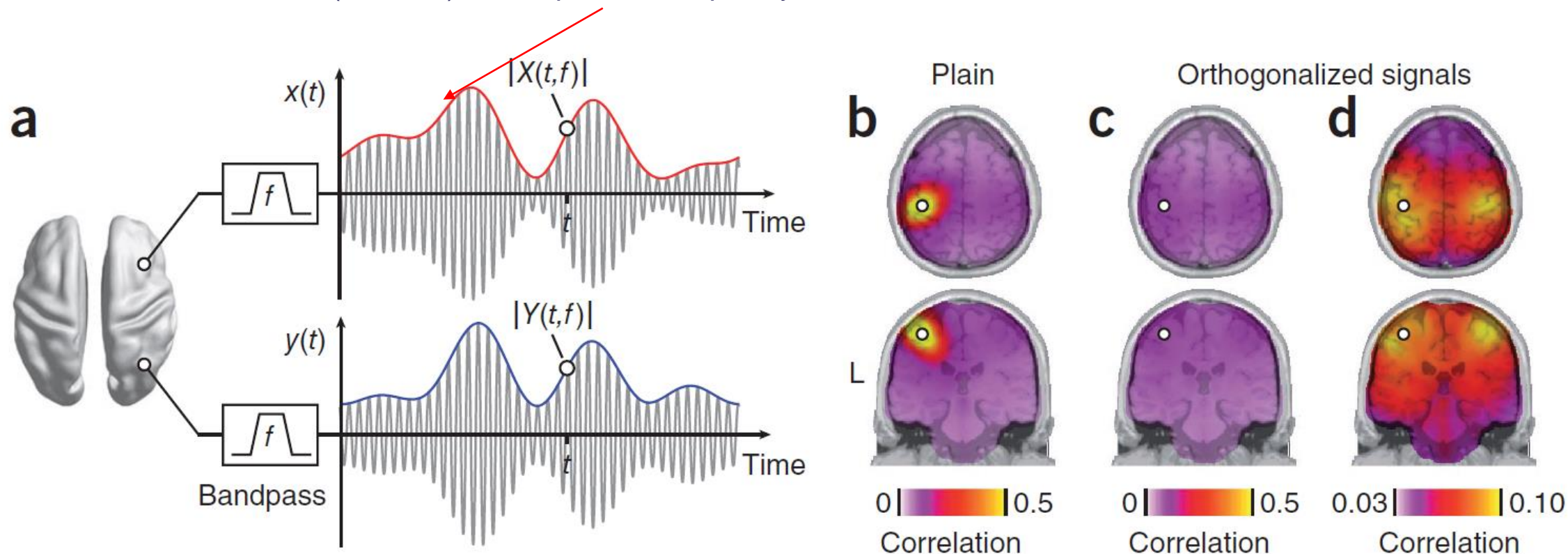
# Temporal Correlation of Timecourses – Resting State

The “Hilbert Envelope” provides a coarser but more robust description of the timecourse.



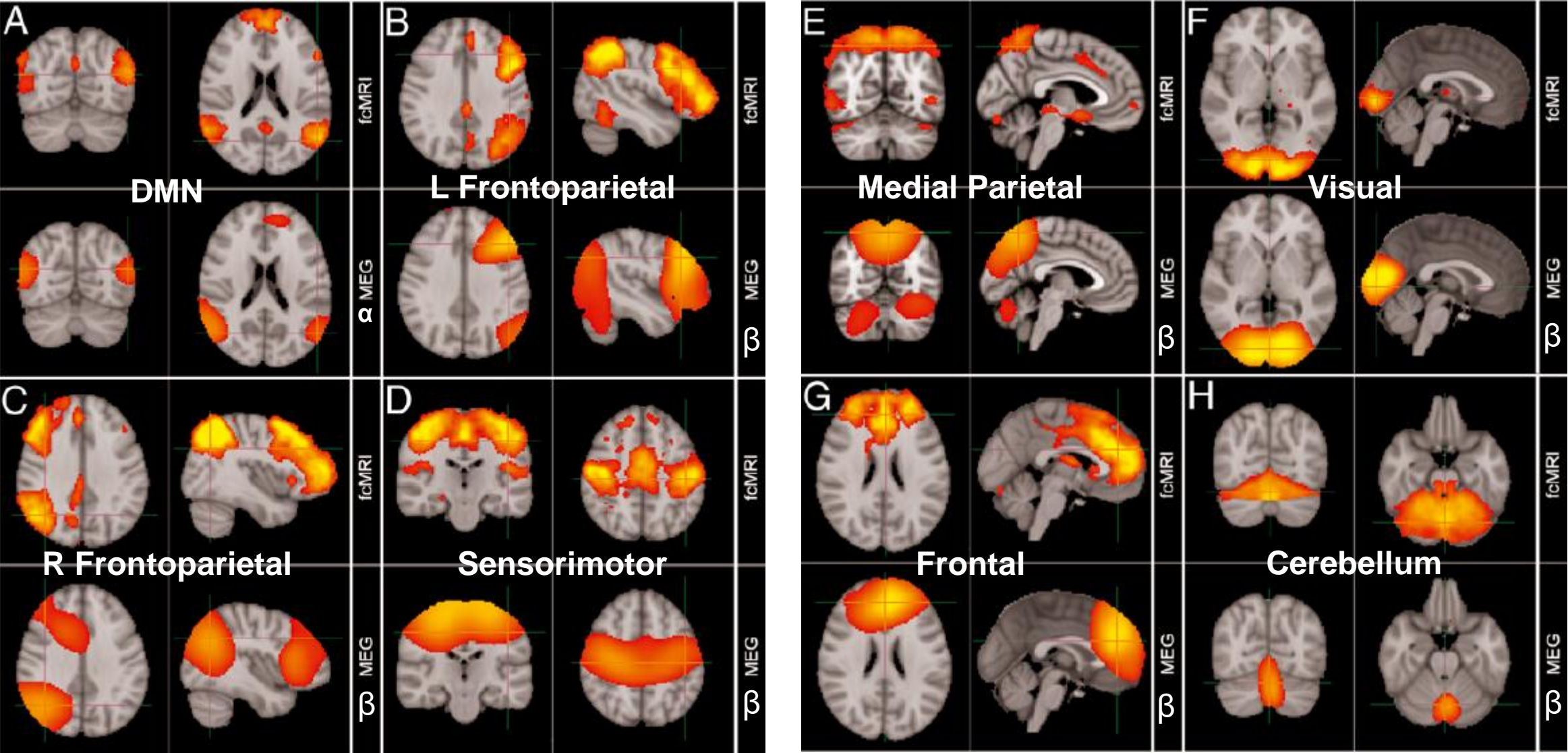
# Functional Connectivity of Resting State Activity

(“Hilbert”) Envelope for a frequency band





# Functional Connectivity of Resting State Activity





# Spectral Connectivity – “Synchronisation”

Neuron  
Perspective

## Rhythms for Cognition: Communication through Coherence

Pascal Fries<sup>1,2,\*</sup>

<https://www.sciencedirect.com/science/article/pii/S0896627315008235>

## Spectral fingerprints of large-scale neuronal interactions

Markus Siegel<sup>1 \*</sup>, Tobias H. Donner<sup>2 \*</sup> and Andreas K. Engel<sup>3</sup>

<https://www.nature.com/articles/nrn3137>

Coupled Oscillators: <https://www.youtube.com/watch?v=T58IGKREubo>

# Phase-Locking

Is the phase difference between signals consistent across trials?

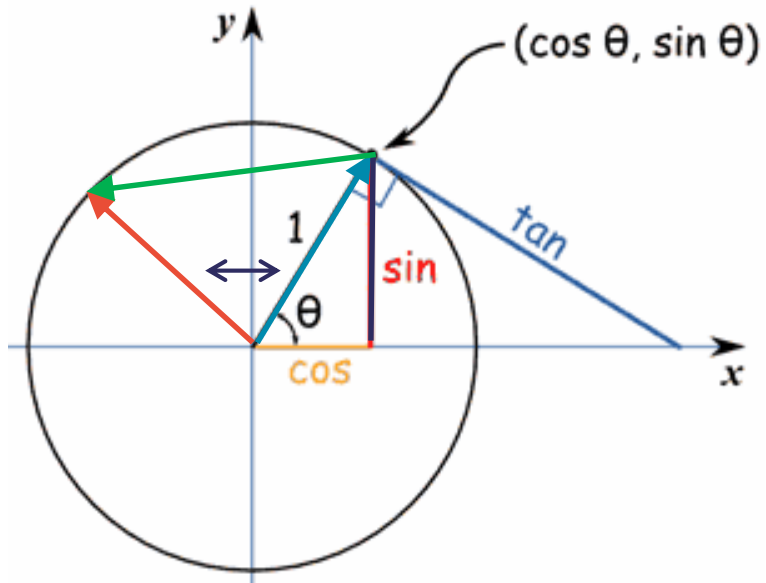
$$s(t) = a * \sin(2\pi f t + \theta)$$

a: amplitude

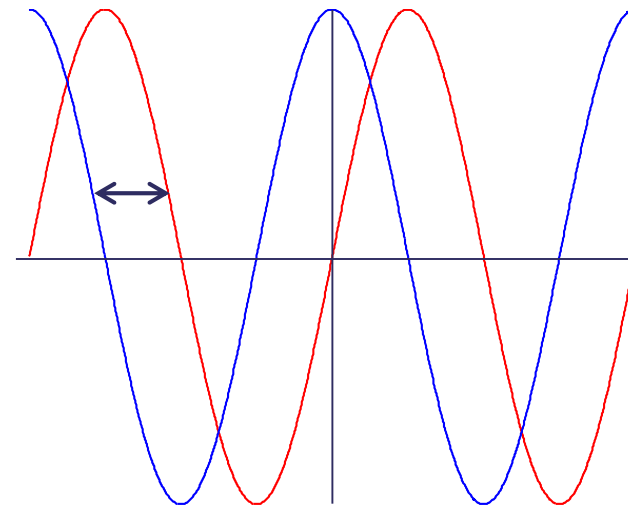
f: frequency

$\theta$  : phase

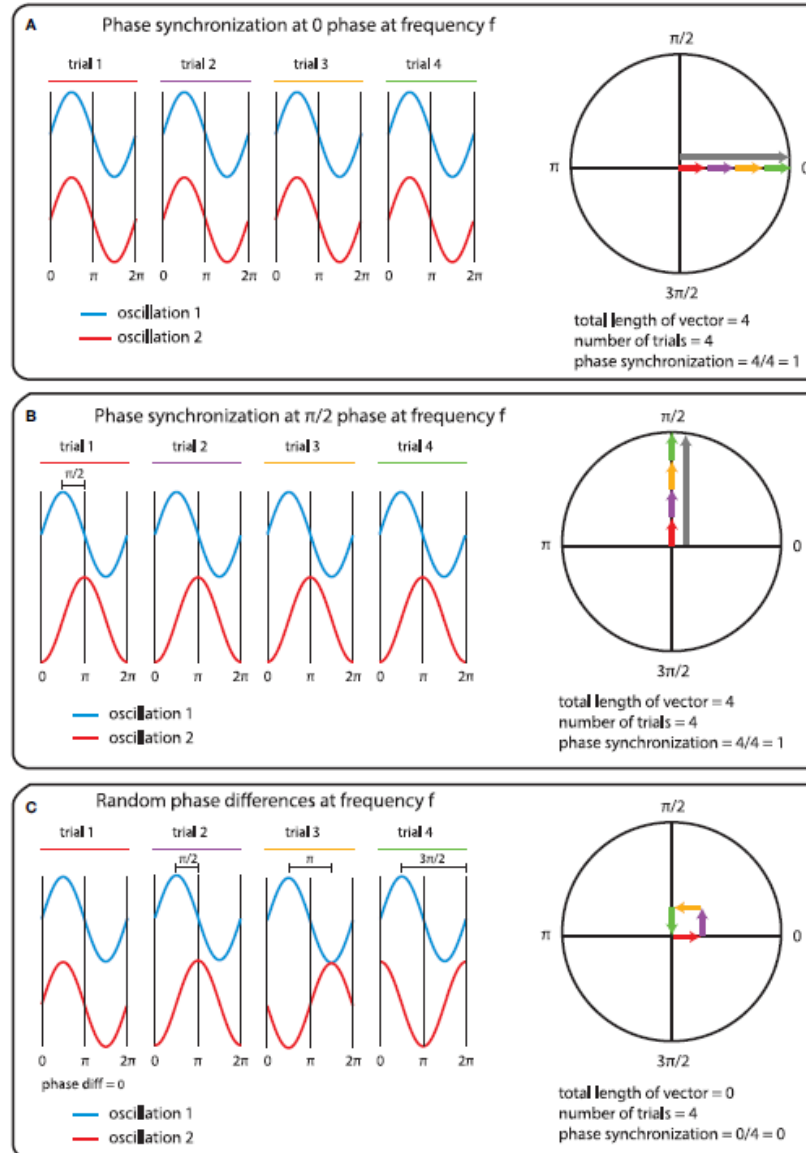
Phase difference in frequency domain



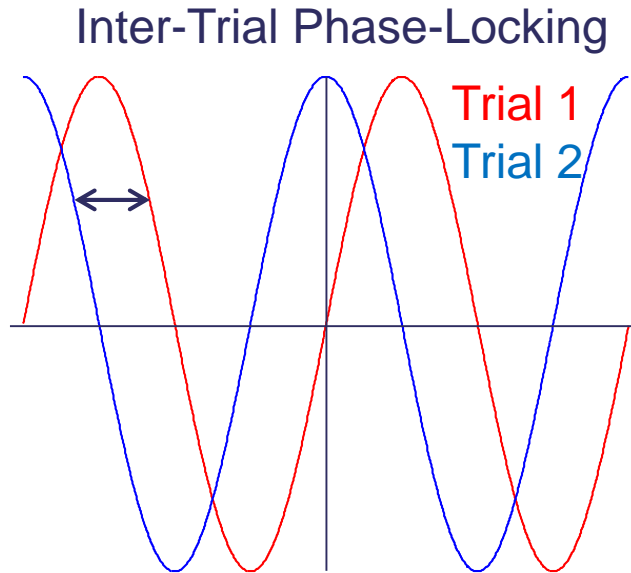
Phase difference in time domain



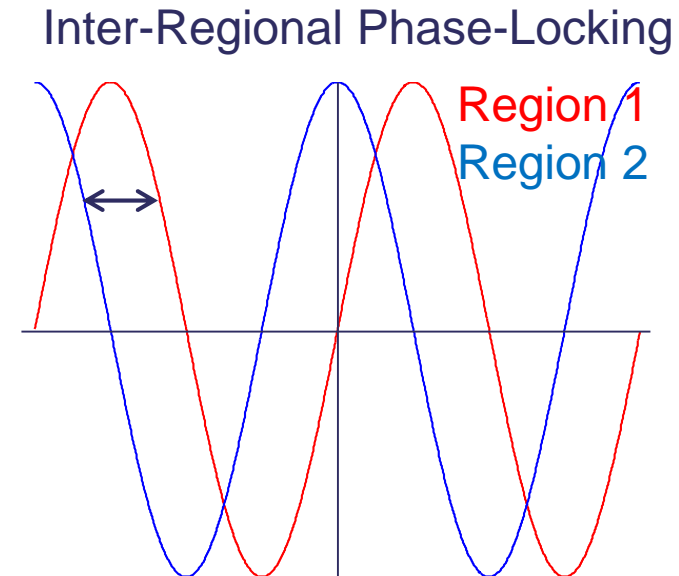
# Phase-Locking – Use Only Phase, Ignore Amplitude



# Different Types of Phase-Locking

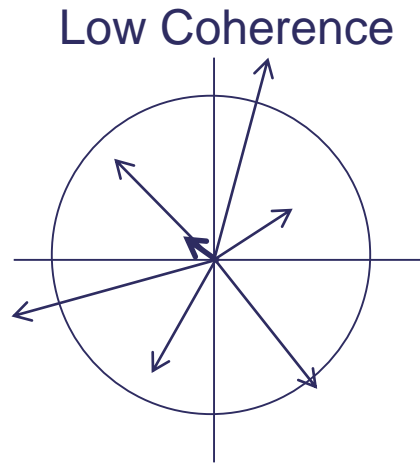


Does the phase at a particular frequency remain stable across trials with one region?  
(not connectivity)

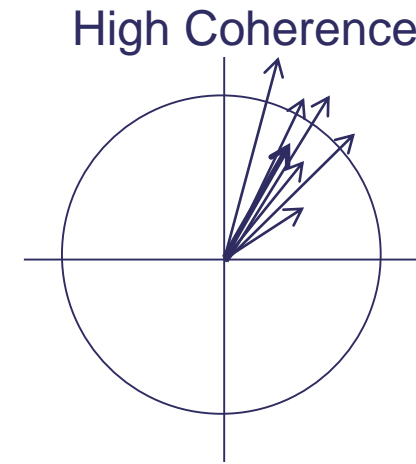


Does the phase difference between two regions at a particular frequency remain stable across trials with one region?  
(connectivity)

# (Magnitude-Squared) Coherence



Every vector represents the amplitude and phase difference of one trial.

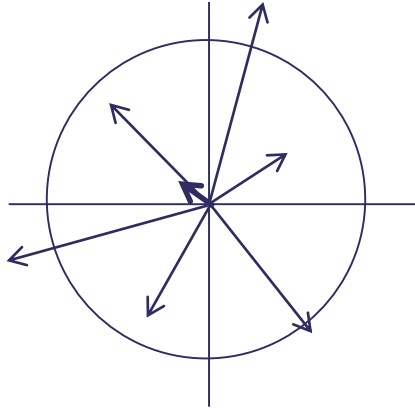


Coherence takes amplitude as well as phase consistency into account. It can be interpreted as “amplitude-weighted phase-locking value”, i.e. trials with low amplitudes are given lower weight than those with higher amplitudes.

If one signal is a time-shifted and re-scaled version of another signal, then their Coherence is 1.  
If two signals are random and independent of each other, then their Coherence is 0.

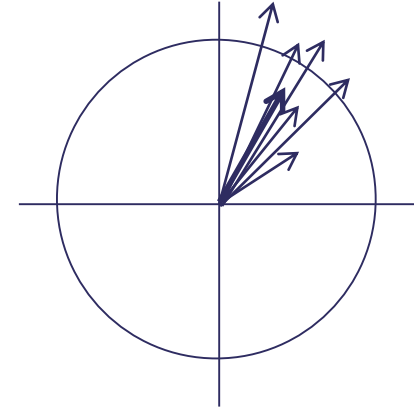
# Phase-Locking vs Coherence

Low Coherence

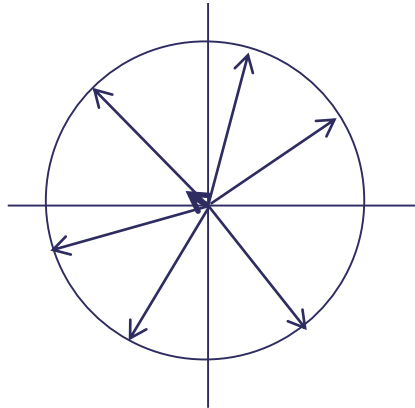


Every vector represents the amplitude and phase difference of one trial.

High Coherence

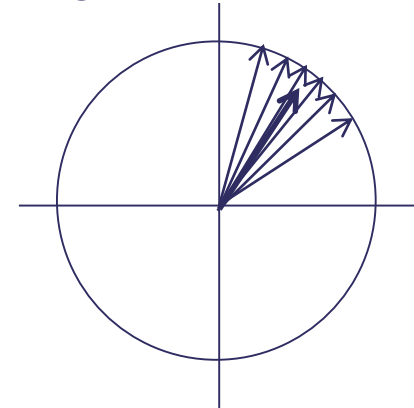


Low Phase-Locking



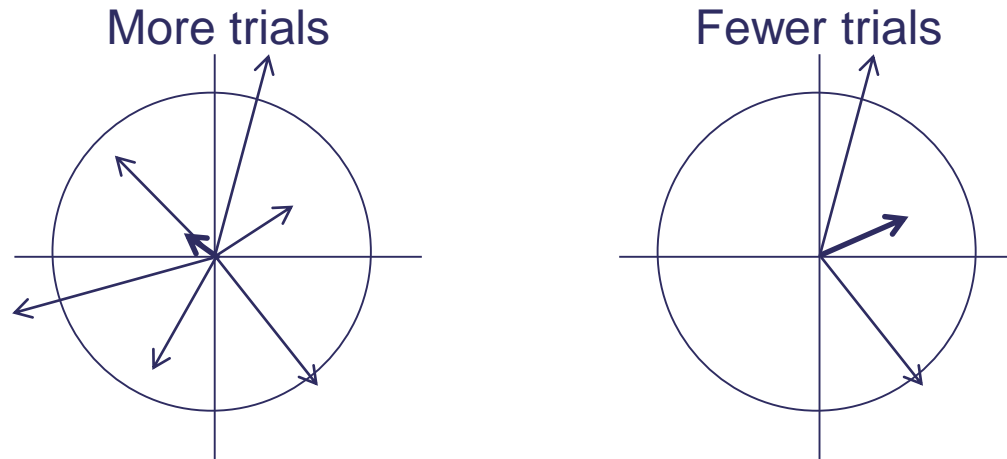
We are not interested in amplitude, and normalise all vectors to unit length. The average vectors measure the phase-consistency across signals (phase-locking value, PLV).

High Phase-Locking





# Sample Size and SNR Bias



Many connectivity metrics are positively biased (e.g. Coherence with values between 0 and 1), i.e. one gets positive values even in the presence of pure noise.

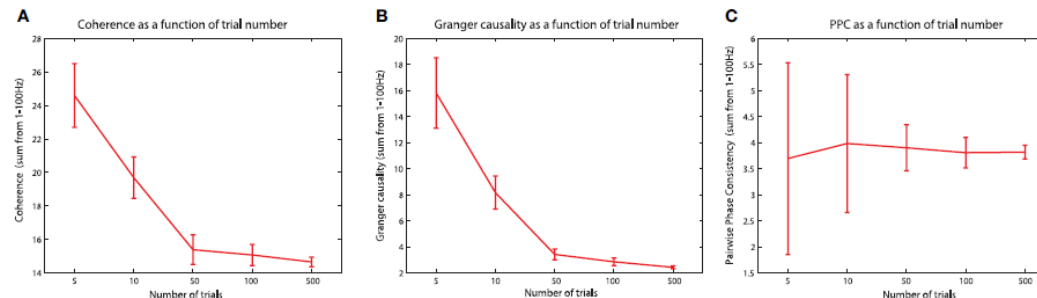
Importantly, the metric depends on the number of trials.

⇒ Plot metric for baseline data and different trials counts in your own data

⇒ Equalise trials counts between conditions

⇒ Baseline correction

This effect is relatively small  
for  $\sim >50$  trials:



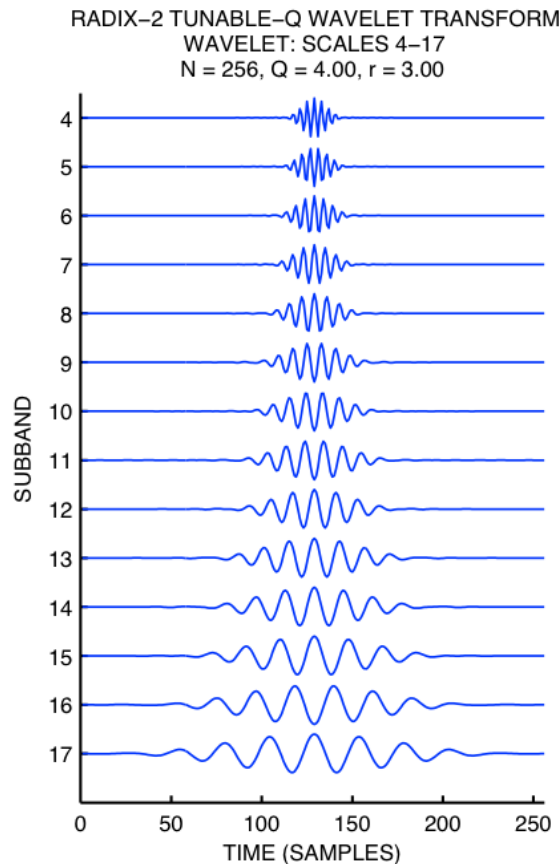
**FIGURE 10 | Sample size bias for coherence and Granger causality estimates.** (A–C) For each respective metric, simulations based on 5, 10, 50, 100, and 500 trials were run, and coherence (A), Granger causality (B), and PPC (C) were calculated. Each panel reflects the average  $\pm 1$  standard deviation across 100 realizations.

Bastos & Schoeffelen, Front Syst Nsc 2016

<https://www.frontiersin.org/articles/10.3389/fnsys.2015.00175/full>

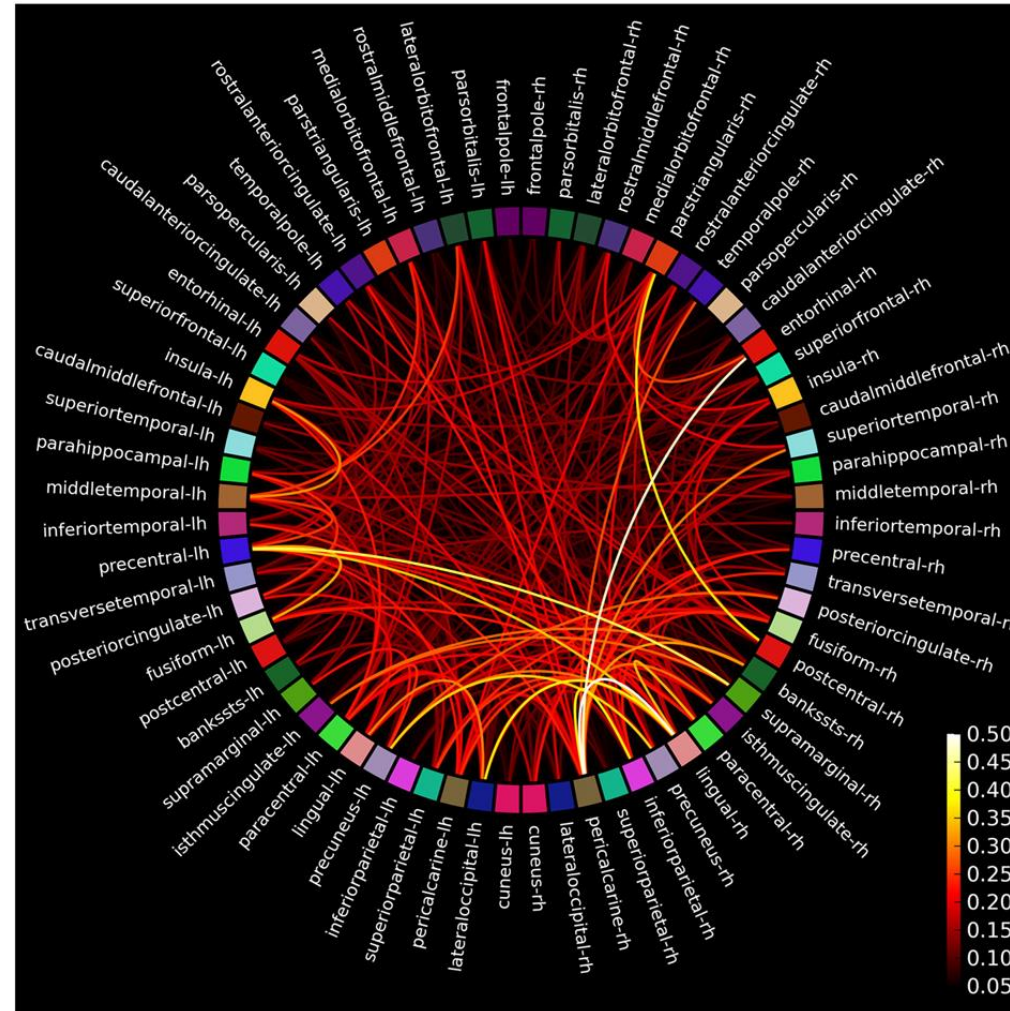
# Time-Resolved Connectivity

Spectral connectivity measures can be computed for separate time windows, or they can be computed continuously using wavelets or Hilbert transform (subject to general trade-off between frequency and time resolution).



Temporal resolution decreases as  
frequency decreases  
(wavelets are getting “broader”)

# Bivariate Functional Connectivity Is Relatively Easy To Compute - And Therefore Suitable For Exploratory “All-To-All” Analyses



Gramfort et al., NI 2014

<https://www.sciencedirect.com/science/article/pii/S1053811913010501>



# Directed Functional Connectivity

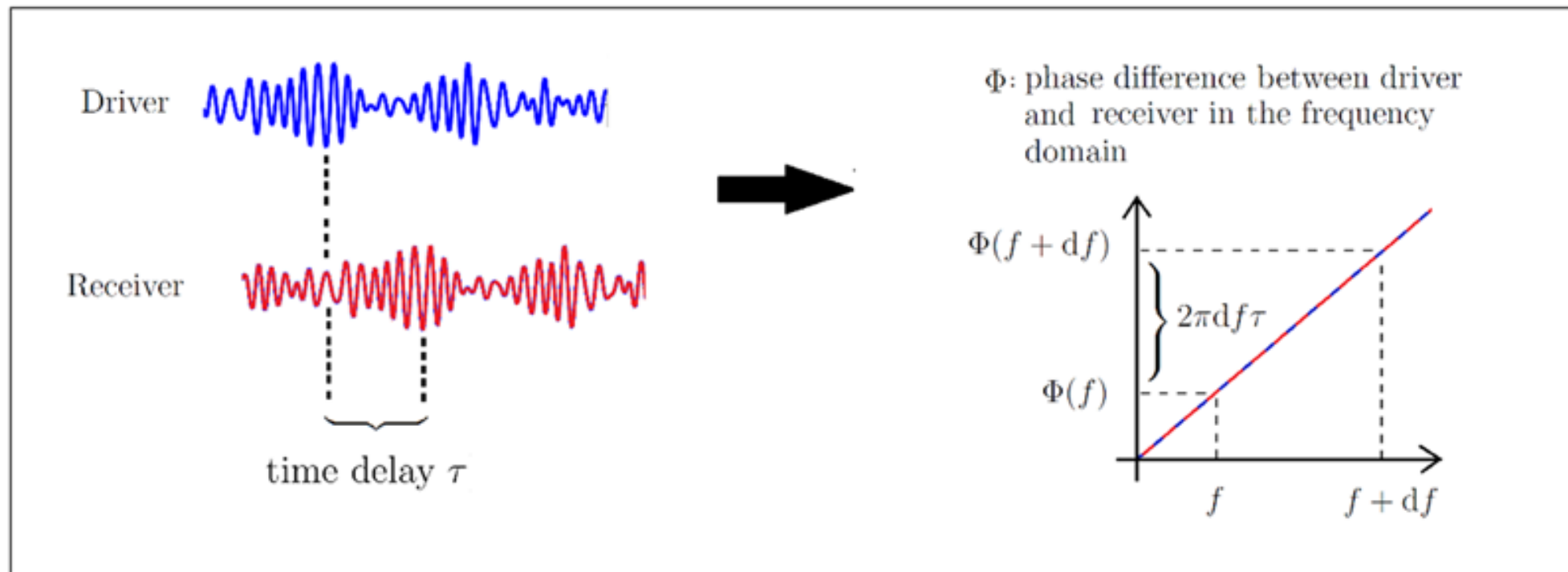
## Phase-Slope Index (PSI):

For signals with a stable time delay, the phase in the frequency domain should depend linearly on frequency

Nolte et al, Phys Rev Let 2008, <http://doc.ml.tu-berlin.de/causality/>

Basti et al., NI 2018, <https://www.sciencedirect.com/science/article/pii/S1053811918301897>

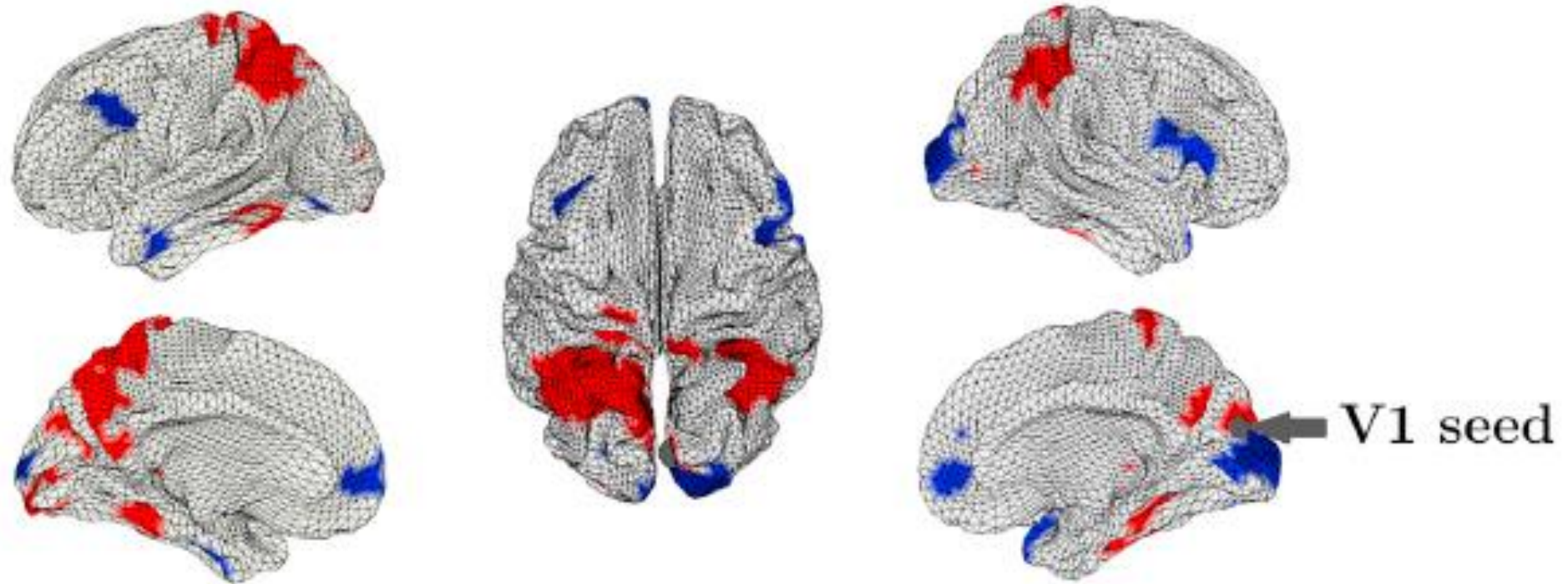
Bastos & Schoeffelen, Front Syst Nsc 2016, <https://www.frontiersin.org/articles/10.3389/fnsys.2015.00175/full>



Basti et al., J Serb Soc Comp Mech 2017

<https://www.scopus.com/record/display.uri?eid=2-s2.0-85044605749&origin=inward>

# Phase Slope Index (PSI)



A-band, HCP resting state data

- Sources which lead V1 ( $FDR < 0.01$ )
- Sources which follow V1 ( $FDR < 0.01$ )



# Directed Functional Connectivity

## **Auto-regressive models, Granger Causality:**

### **...in the time domain:**

Predict the future of a signal based on the past of its own and other signals

### **...in the frequency domain:**

- Partial Directed Coherence
- Directed Transfer Function

Bastos & Schoeffelen, Front Syst Nsc 2016, <https://www.frontiersin.org/articles/10.3389/fnsys.2015.00175/full>

Greenblatt et al., J Nsc Meth 2012, <https://www.sciencedirect.com/science/article/pii/S0165027012000817>

Haufe et al. NI 2013, <https://www.sciencedirect.com/science/article/pii/S1053811912009469>



MRC Cognition  
and Brain  
Sciences Unit



UNIVERSITY OF  
CAMBRIDGE

# Thank you