EEG/MEG 3:

Functional Connectivity Analysis

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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

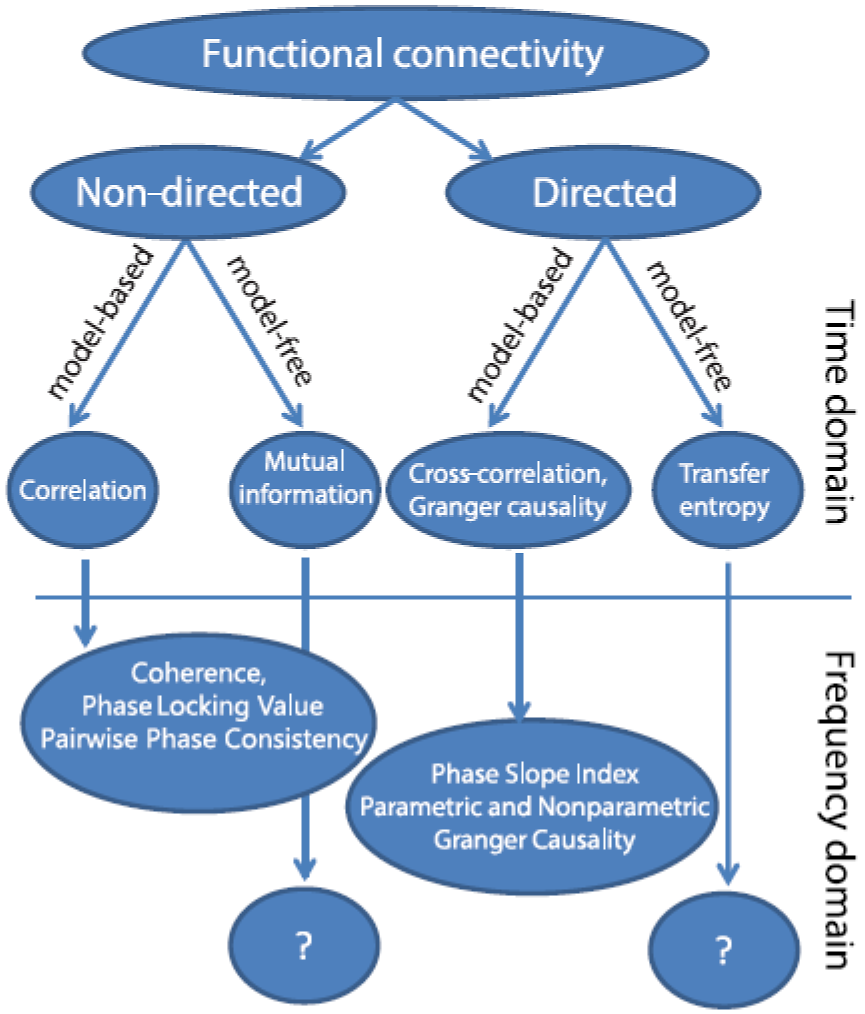
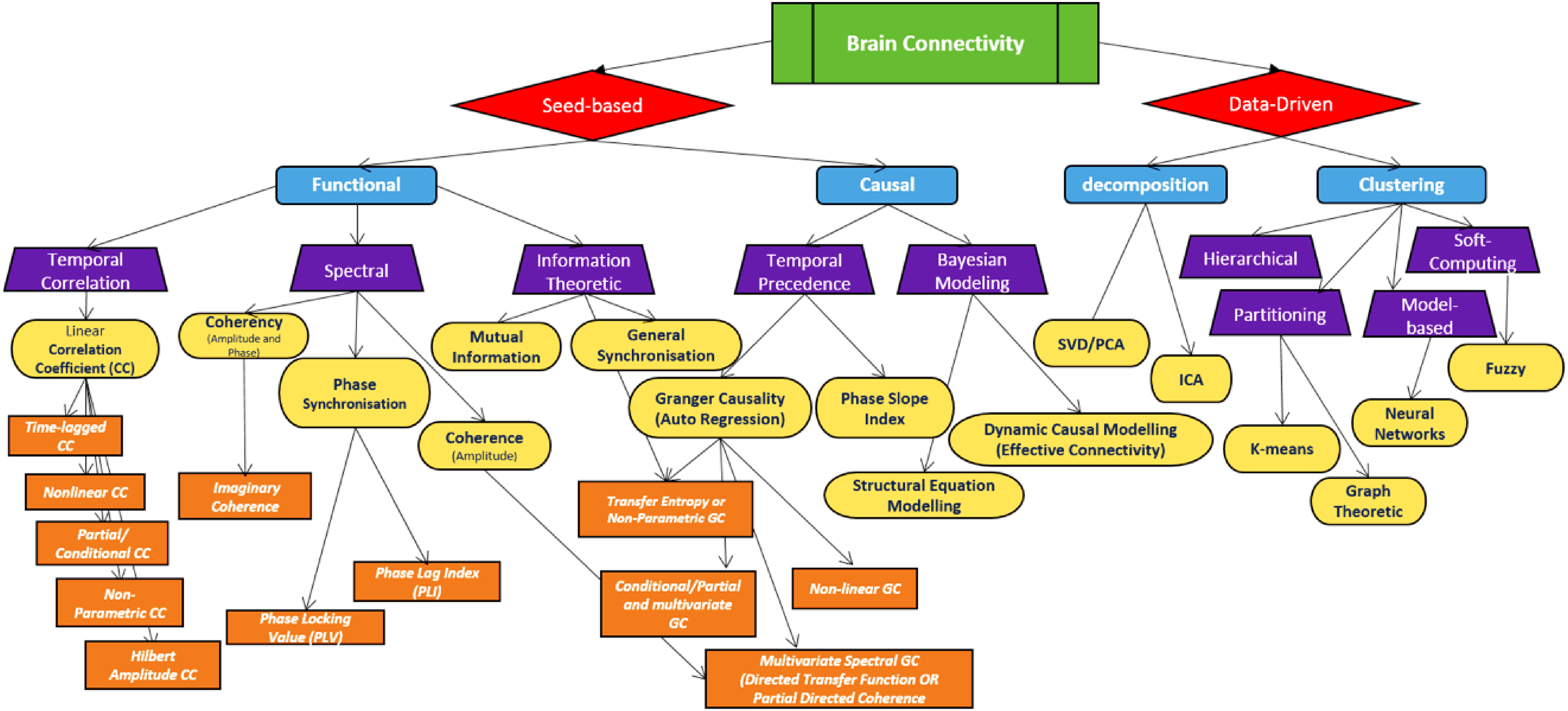


FIGURE 1 | A taxonomy of popular methods for quantifying functional connectivity.

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

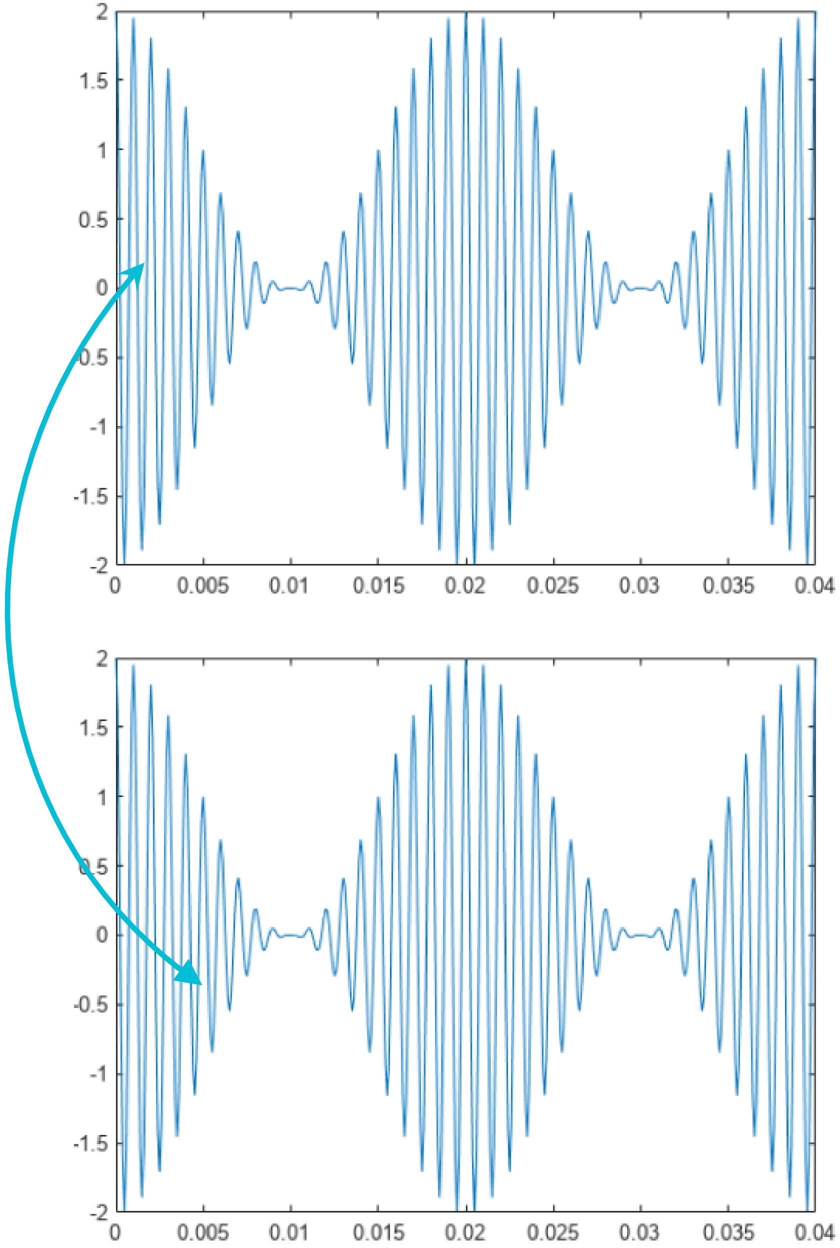
“Brain Connectivity”



From Farahibozorg, PhD Thesis 2018

Temporal Correlation of Timecourses

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

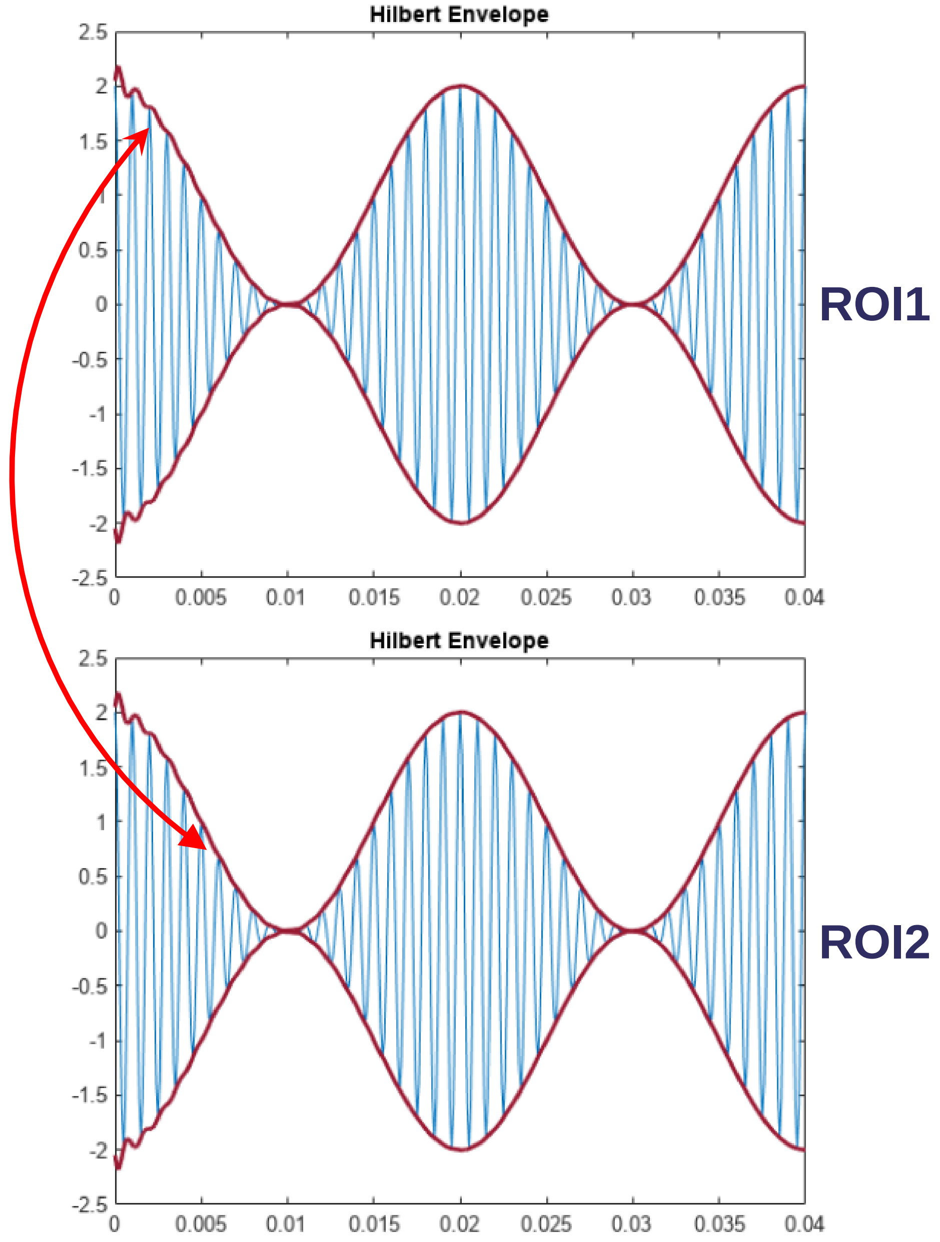


ROI1

ROI2

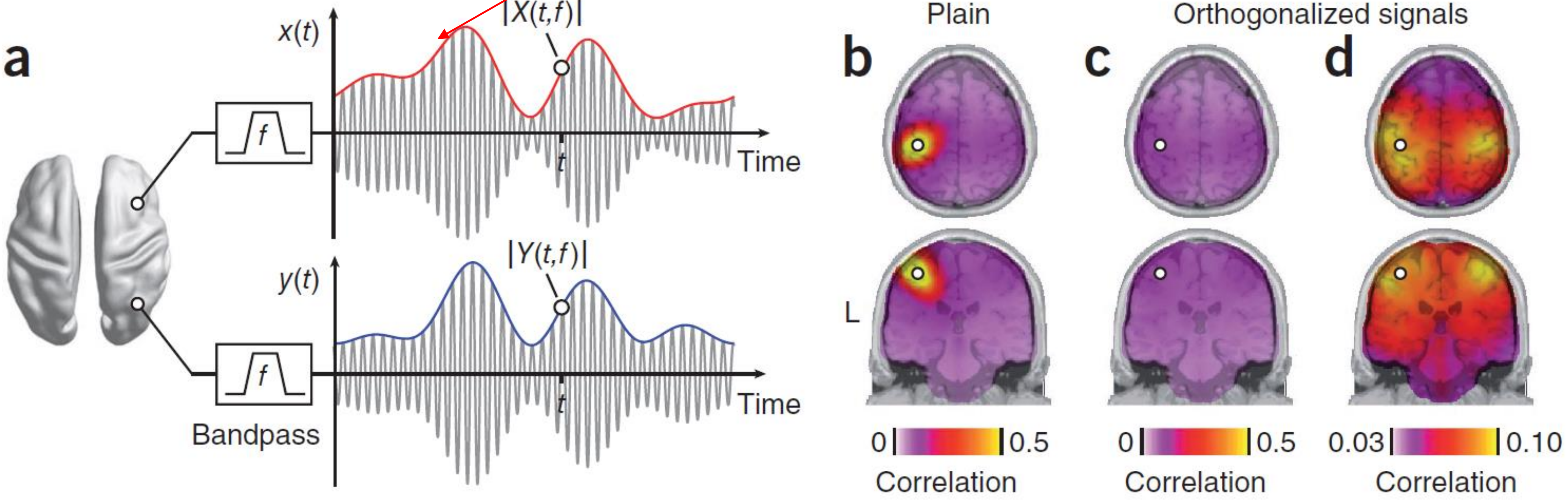
Temporal Correlation of Timecourses – Resting State

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



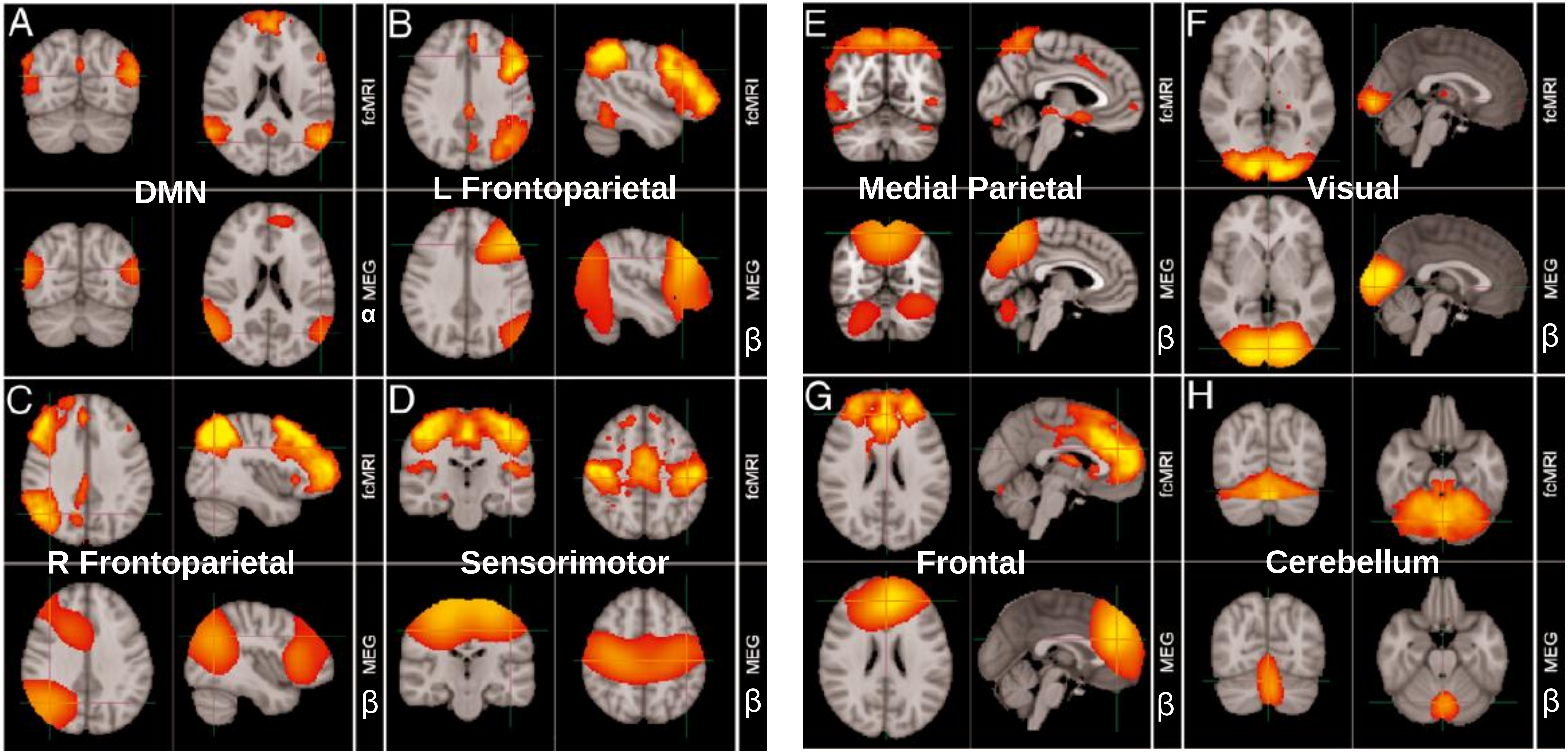
Functional Connectivity of Resting State Activity

(“Hilbert”) Envelope for a frequency band



Hipp et al., Nat Nsc 2012, https://www.nature.com/articles/nn.3101

Functional Connectivity of Resting State Activity



Brooks et al., PNAS 2011, https://www.pnas.org/doi/10.1073/pnas.1112685108

Spectral Connectivity – “Synchronisation”

Neuron
Perspective

Rhythms for Cognition: Communication through Coherence

Pascal Fries[1,2,*]

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

Spectral fingerprints of large-scale neuronal interactions

Markus Siegel[1], Tobias H. Donner[2]* and Andreas K. Engel[3]*

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

Coupled Oscillators: https://www.youtube.com/watch?v=T58lGKREubo

Phase-Locking

Is the phase difference between signals consistent across trials?

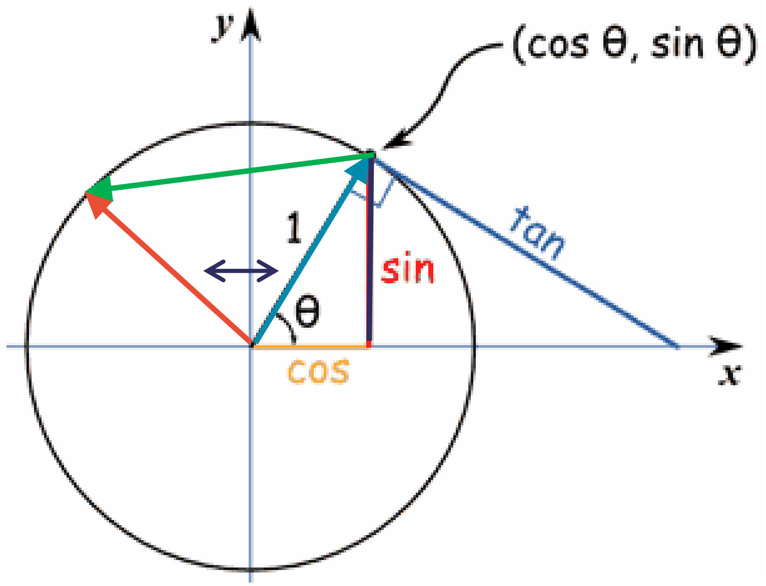
$$s(t) = a * sin(2\pi f t + \theta)$$

a: amplitude

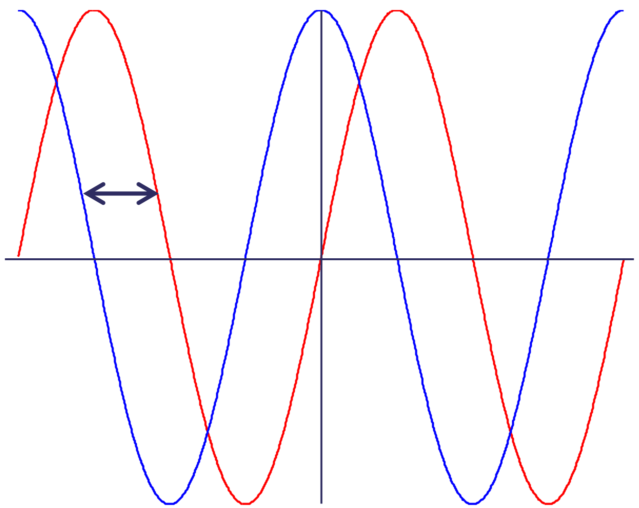
f: frequency

θ : phase

Phase difference in frequency domain

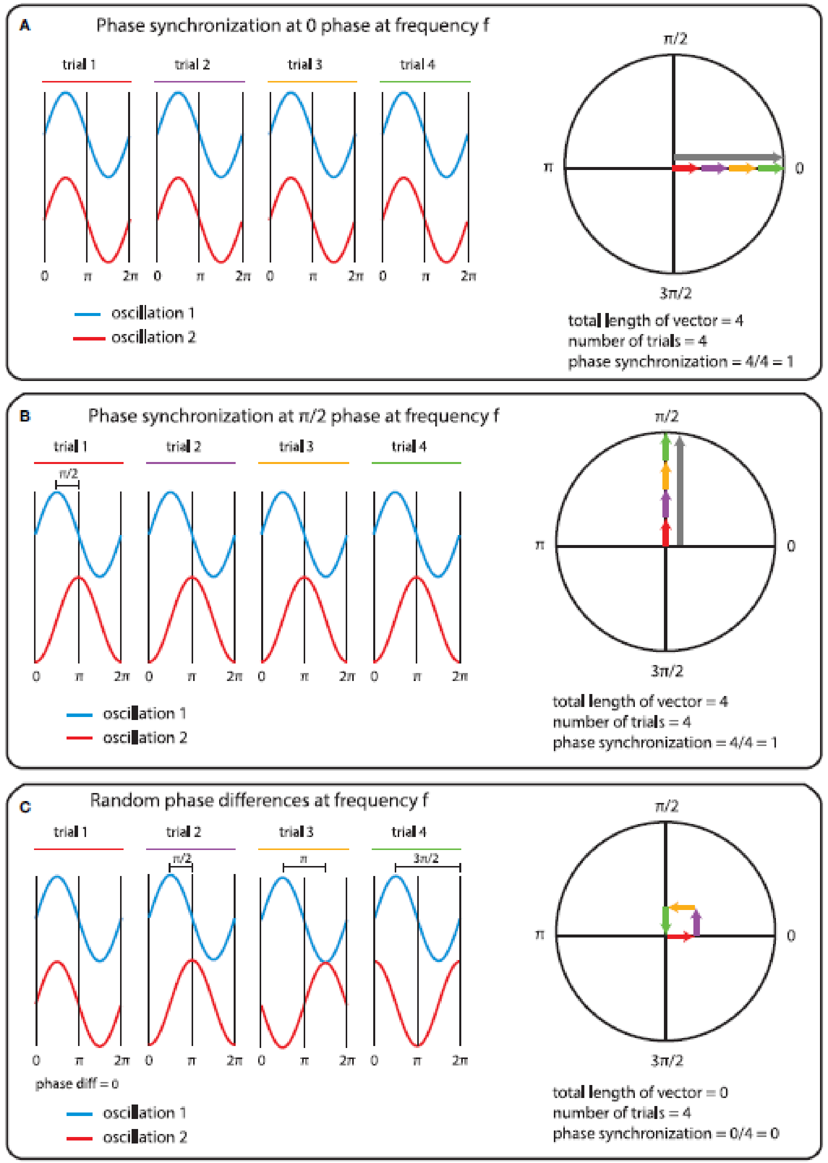


Phase difference in time domain



Lachaux et al., HBM 1999: http://www.ncbi.nlm.nih.gov/pubmed/10619414

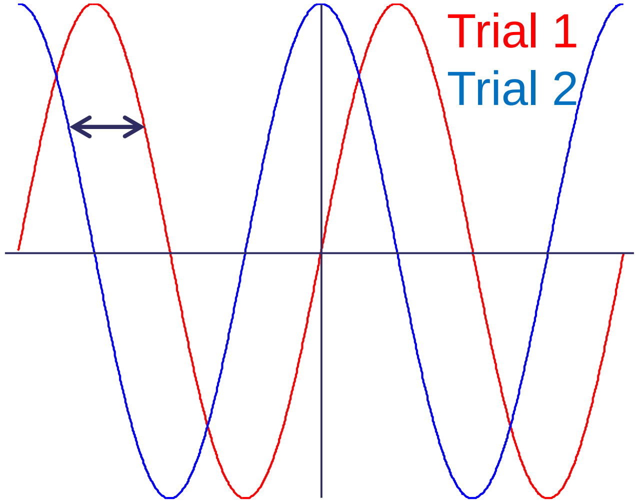
Phase-Locking – Use Only Phase, Ignore Amplitude



e.g., Bastos & Schoeffelen, Front Syst Nsc 2016, Fig. 3
https://www.frontiersin.org/articles/10.3389/fnsys.2015.00175/full

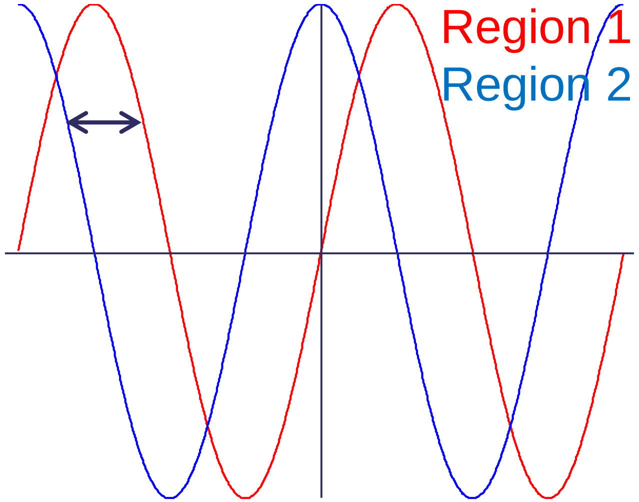
Different Types of Phase-Locking

Inter-Trial Phase-Locking



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

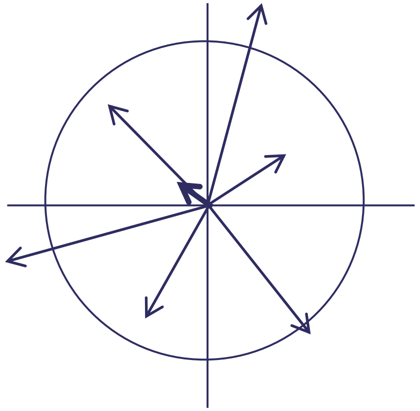
Inter-Regional Phase-Locking



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

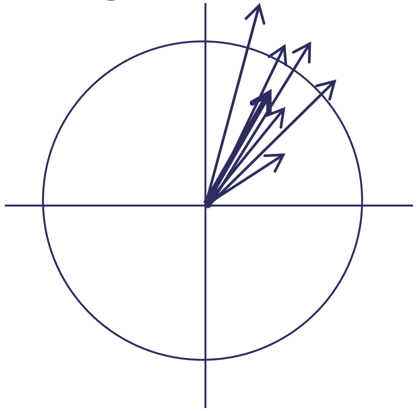
(Magnitude-Squared) Coherence

Low Coherence



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

High Coherence



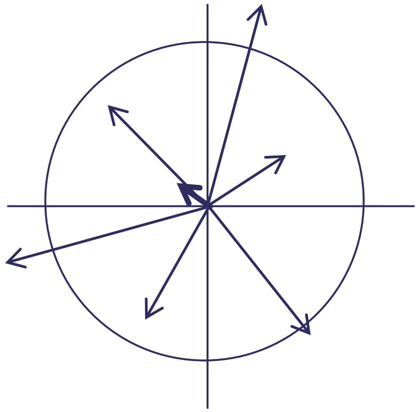
Coherence takes amplitude as well as phase consistency into account.
It can be interpreted as “amplitude-weighted phase-locking value”, i.e. trials with low amplitudes are given lower weight than those with higher amplitudes.

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.

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

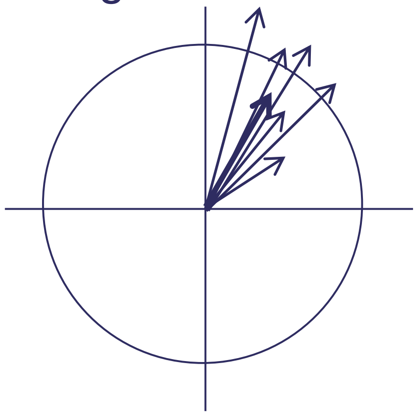
Phase-Locking vs Coherence

Low Coherence

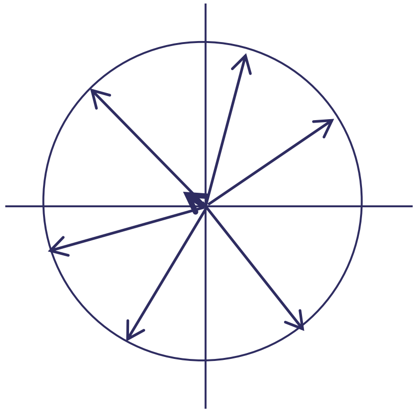


Every vector represents the amplitude and phase difference of one trial.

High Coherence

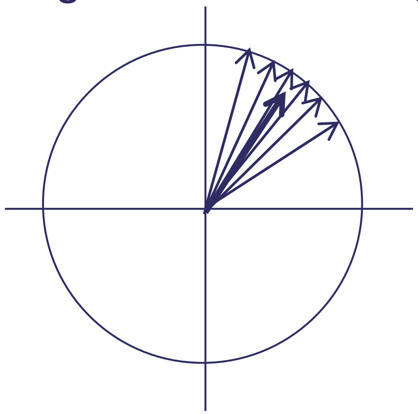


Low Phase-Locking

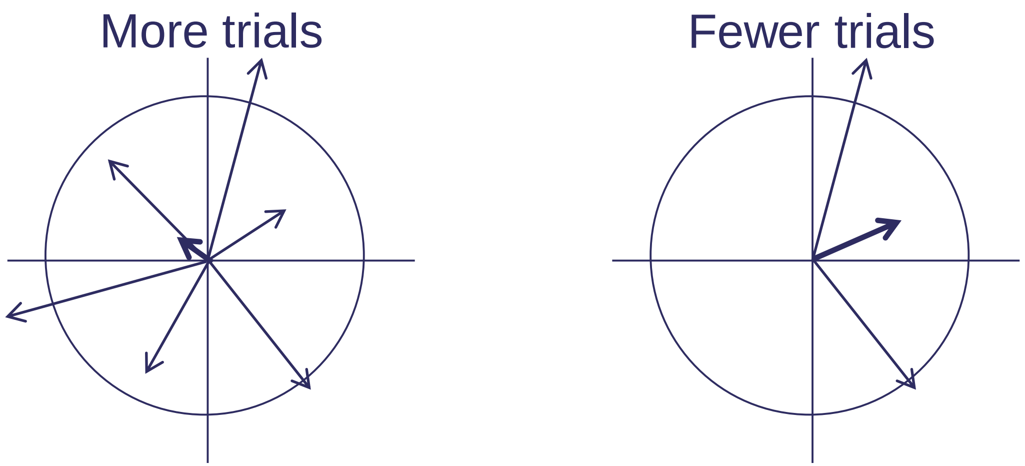


We are not interested in amplitude, and normalise all vectors to unit length. The average vectors measure the phase-consistency across signals (phase-locking value, PLV).

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 ~>50 trials:

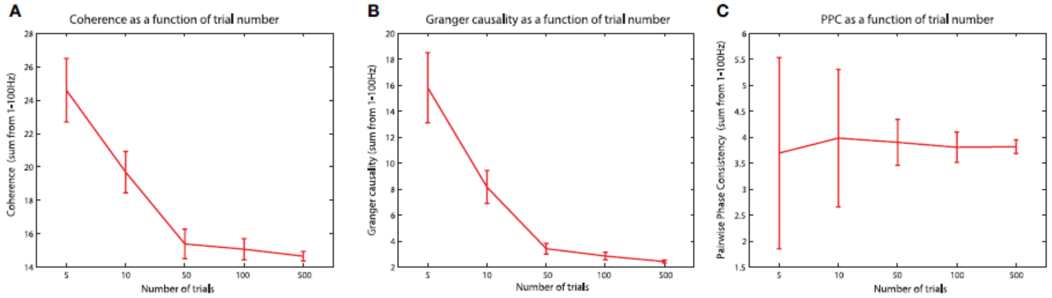
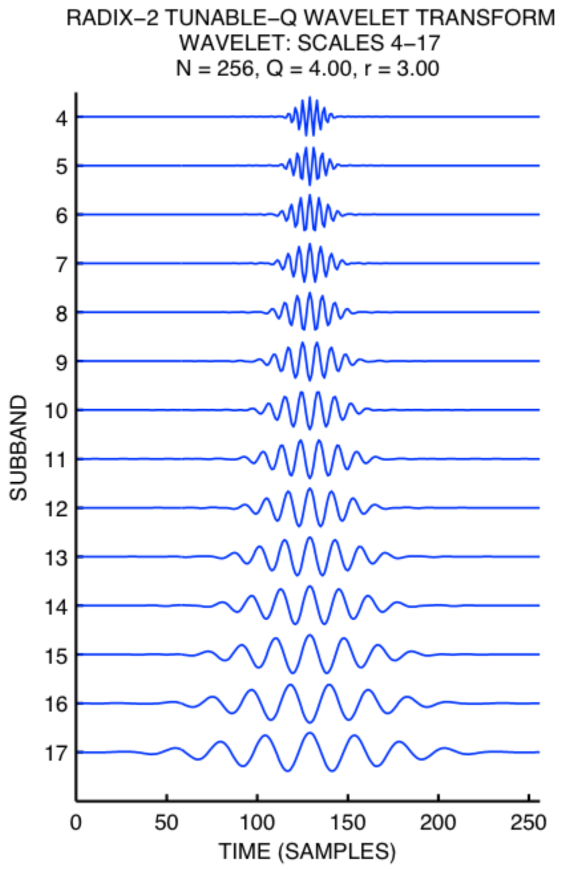


FIGURE 10 | Sample size bias for coherence and Granger causality estimates. (A–C) For each respective metric, simulations based on 5, 10, 50, 100, and 500 trials were run, and coherence **(A)**, Granger causality **(B)**, and PPC **(C)** were calculated. Each panel reflects the average ± 1 standard deviation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

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

Time-Resolved Connectivity

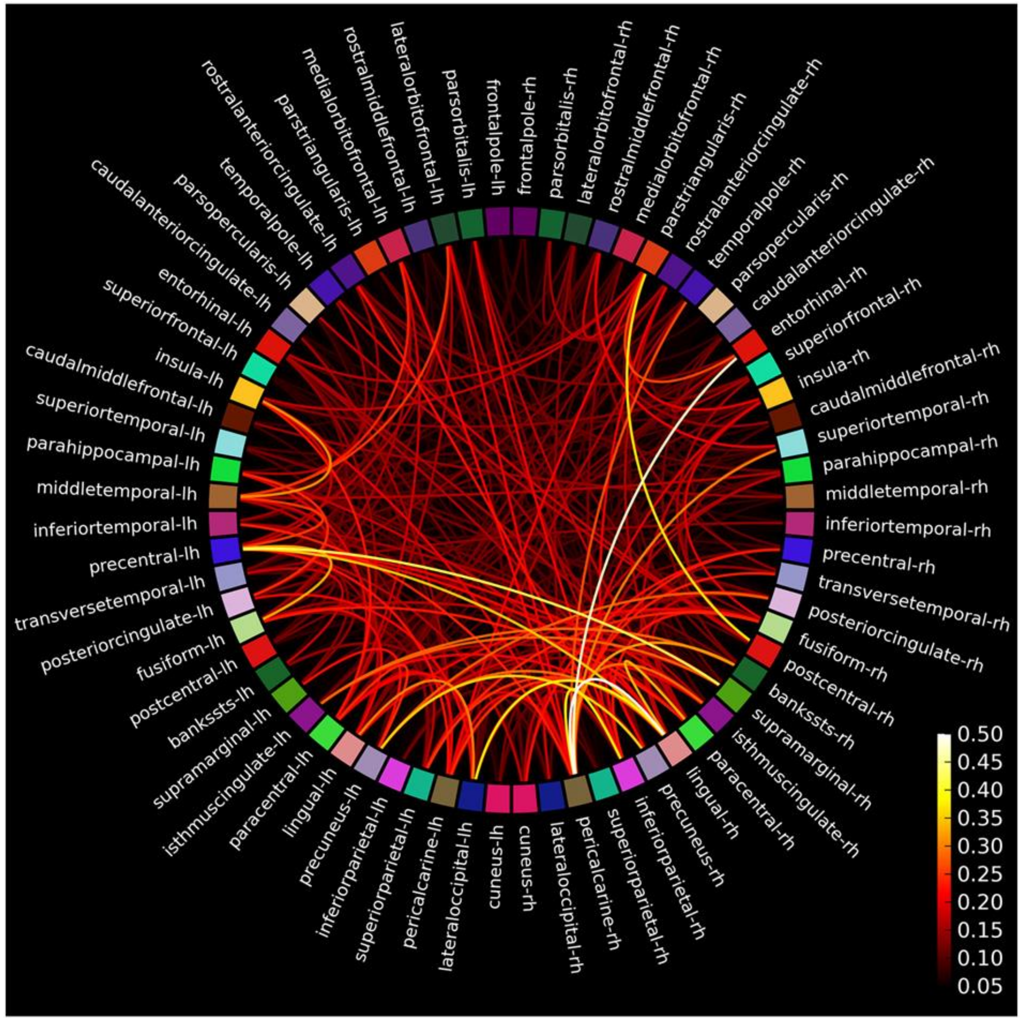
Spectral connectivity measures can be computed for separate time windows, or they can be computed continuously using wavelets or Hilbert transform (subject to general trade-off between frequency and time resolution).



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



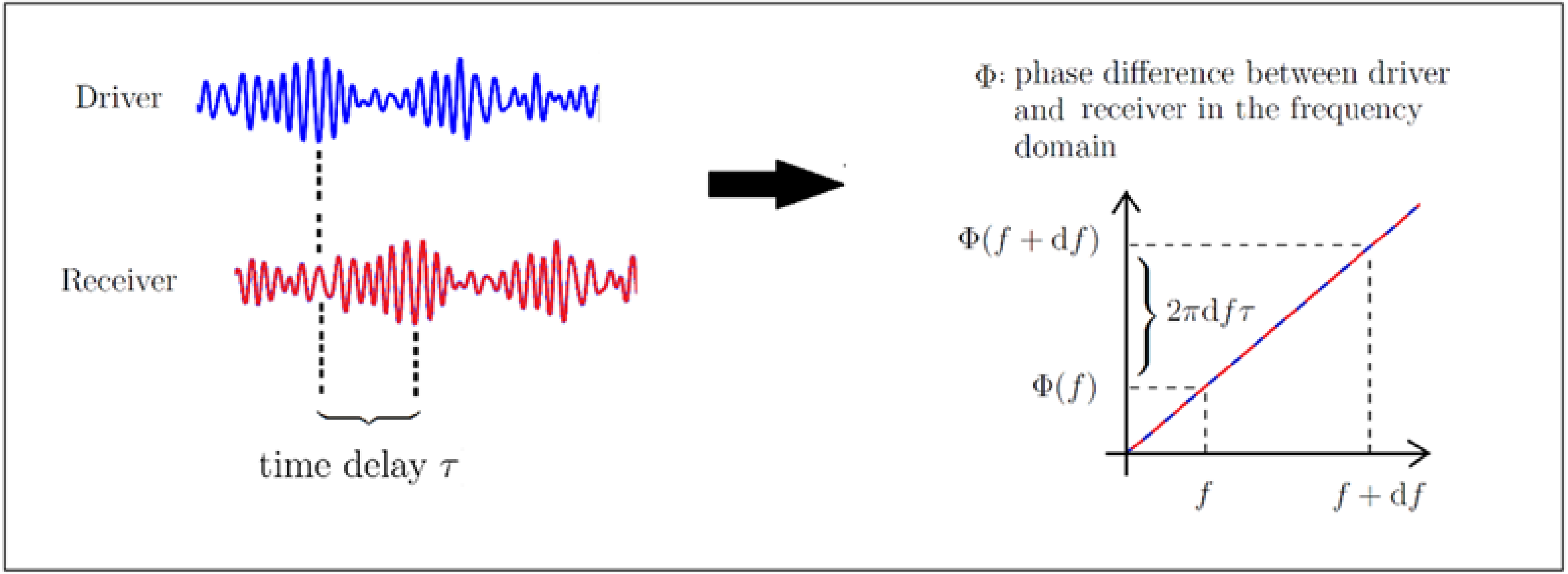
Gramfort et al., NI 2014
https://www.sciencedirect.com/science/article/pii/S1053811913010501

Directed Functional Connectivity

Phase-Slope Index (PSI):

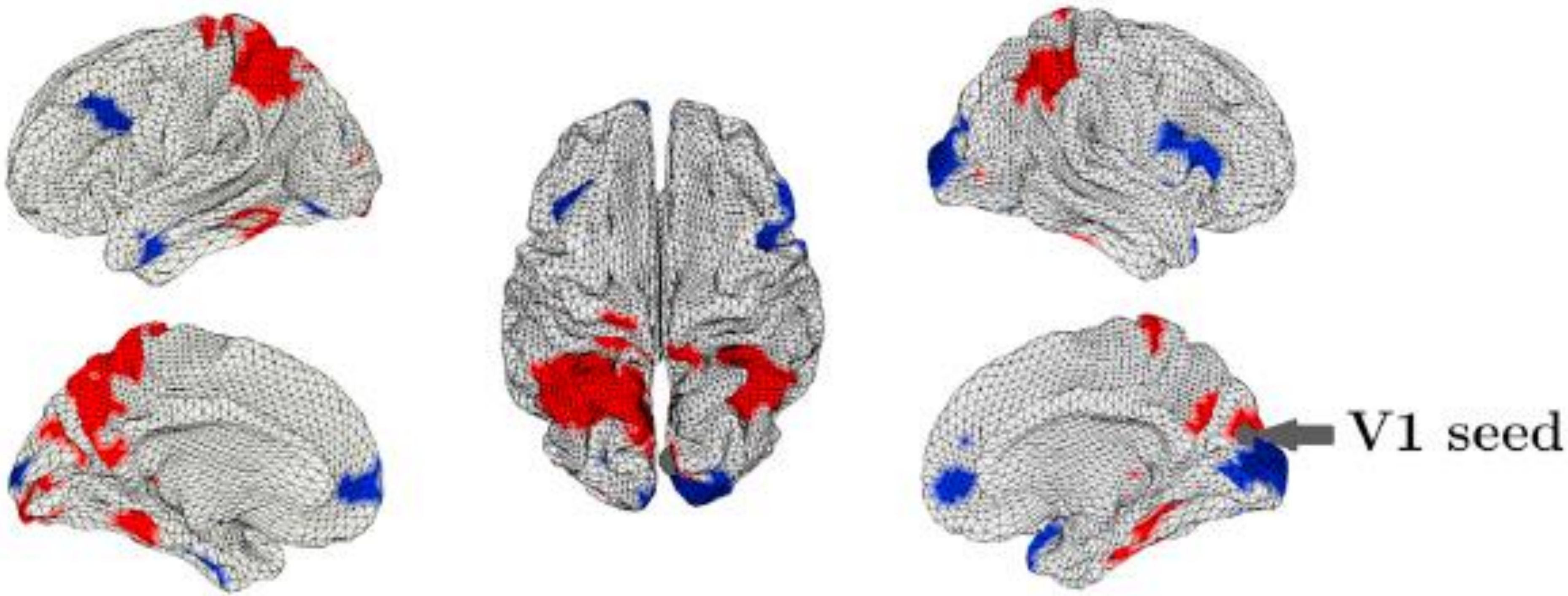
For signals with a stable time delay, the phase in the frequency domain should depend linearly on frequency

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)



■ Sources which lead V1 (FDR<0.01)

■ Sources which follow V1 (FDR<0.01)

A-band, HCP resting state data

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

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

Thank you