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

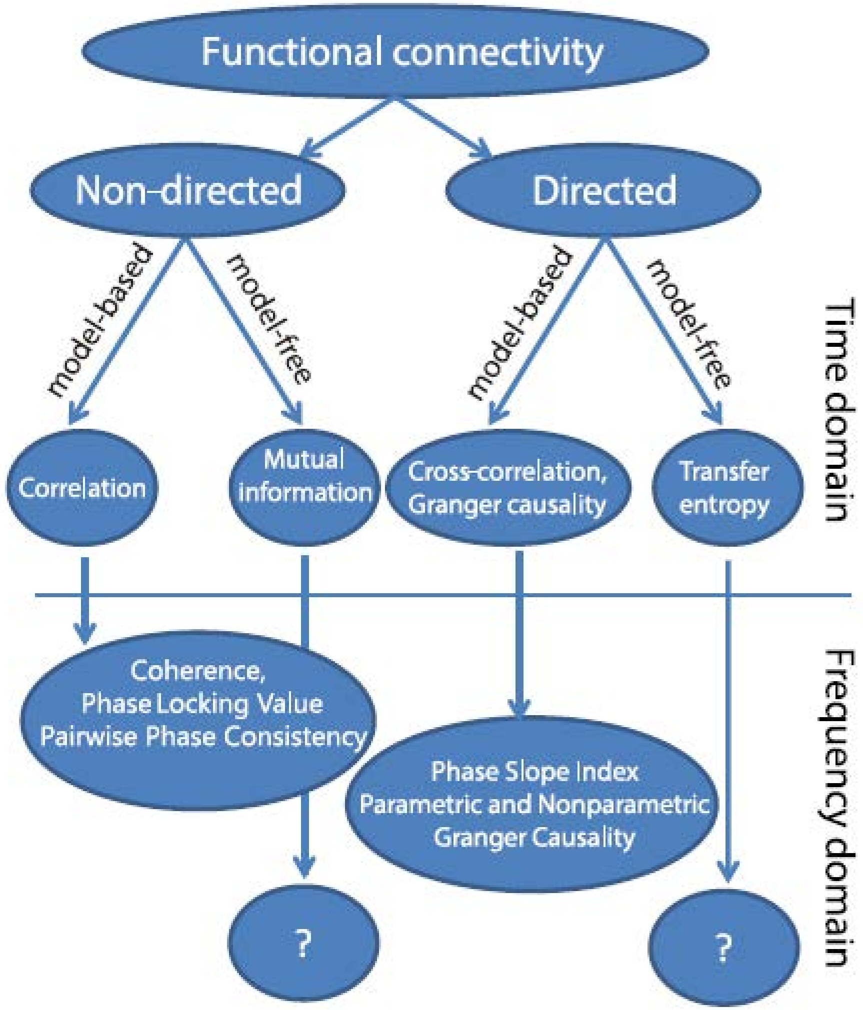
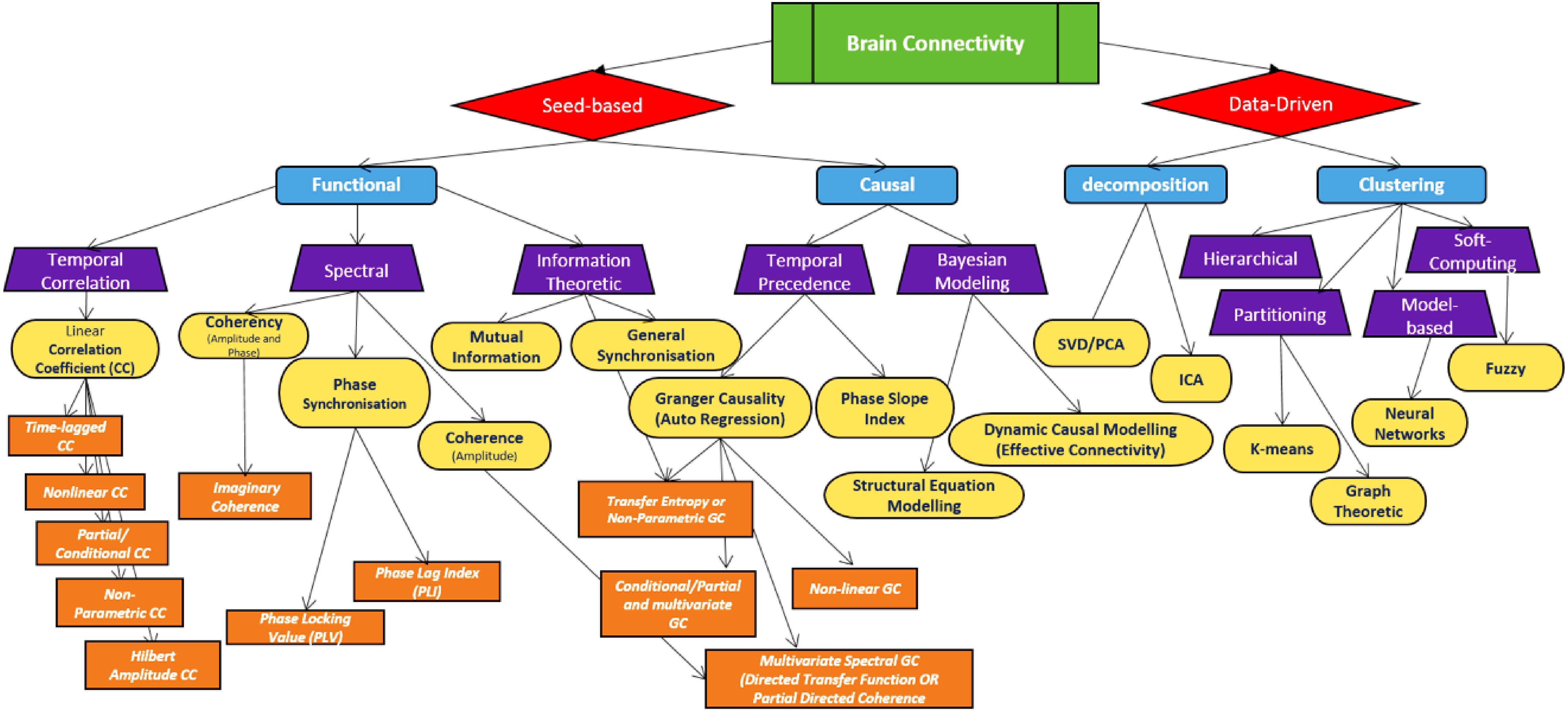


FIGURE 1 | A taxonomy of popular methods for quantifying functional connectivity.

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

“Brain Connectivity”



From Farahibozorg, PhD Thesis 2018

(Magnitude-Squared) Coherence

For two signals x(t) and y(t) at frequency f:

$$C_{xy}(\text{f}) = \frac{|G_{xy}(f)|^2}{G_{xx}(f)G_{yy}(f)}$$

$G_{xx}(f)$ *is power at* f *of* $x(t)$.

$|G_{xy}(f)|^2$ *is cross − spectral density of* $x(t)$ and y(t).

$G_{xy}(f)$ is also called “Coherency” (and can be a complex number).

(MS-)Coherence yields the shared variance of two signals at a given frequency.

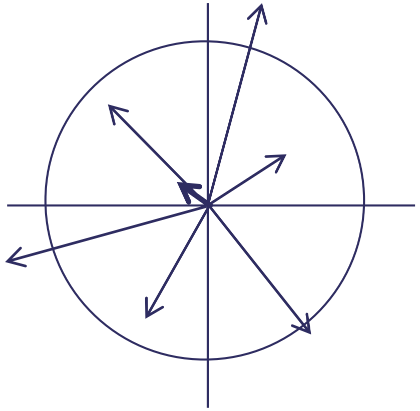
C_{xy}(f)=1: Signals perfectly coherent at frequency f.

C_{xy}(f)=0: Signals not coherent at all at frequency f.

This looks a bit like a correlation – but in this case it depends on amplitude and phase of the signals at frequency f.

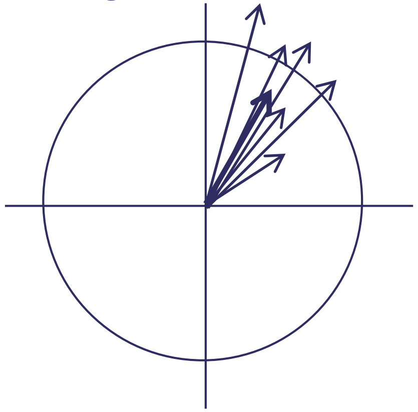
(Magnitude-Squared) Coherence

Low Coherence



Every vector represents the amplitude and phase of one signal
(e.g. phase difference between two regions across trials).

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.

Down to earth:
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 – Use Only Phase, Ignore Amplitude

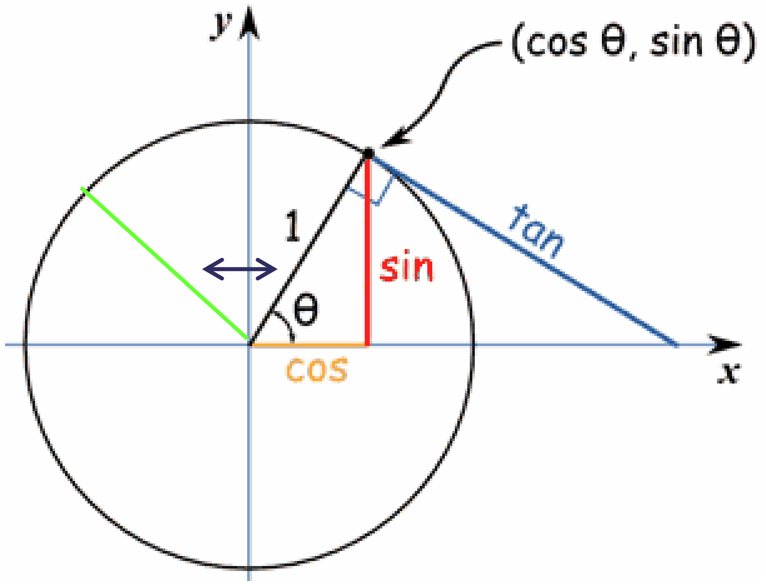
$$s(t) = a * sin(2\pi f t + \theta)$$

a: amplitude

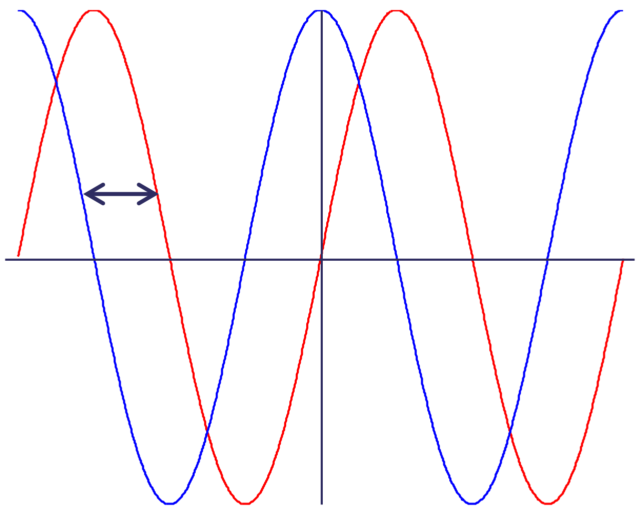
f: frequency

θ : phase

Phase difference in frequency domain

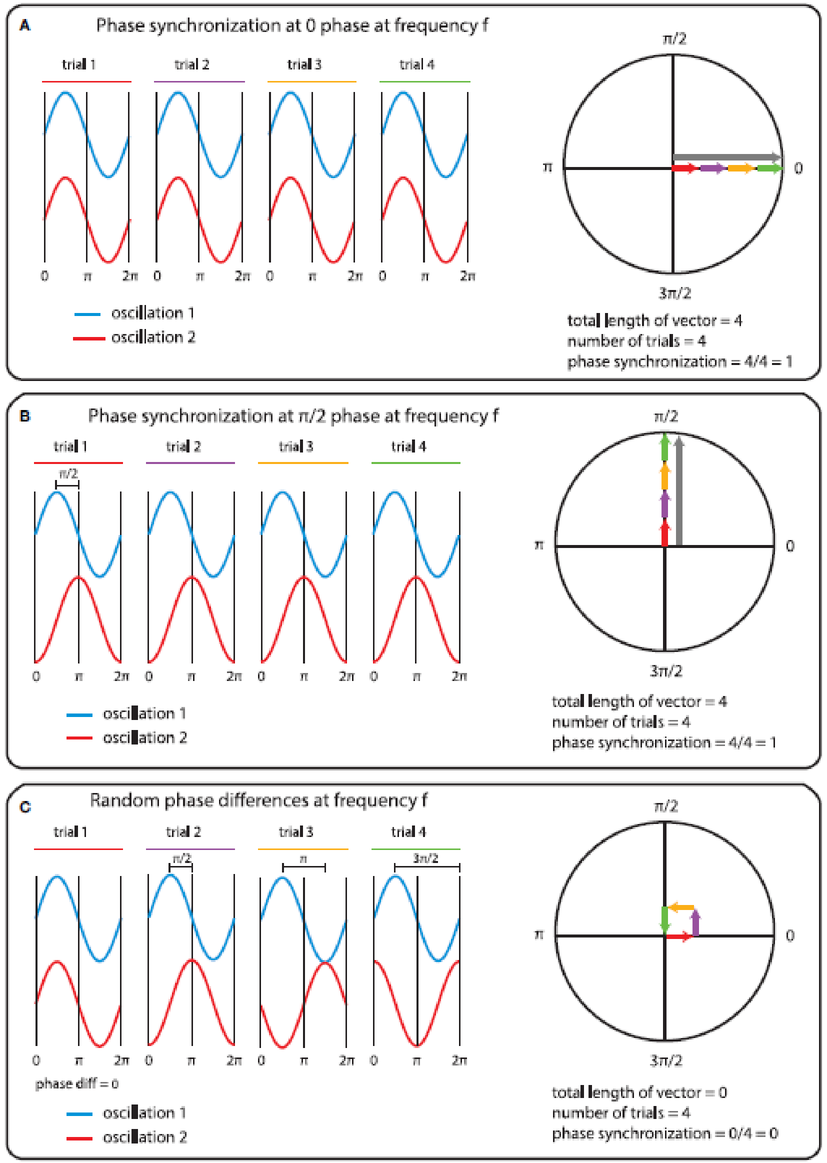


Phase difference in time domain



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

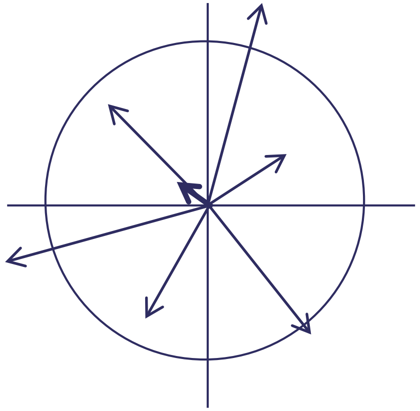
Phase-Locking – Use Only Phase, Ignore Amplitude



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

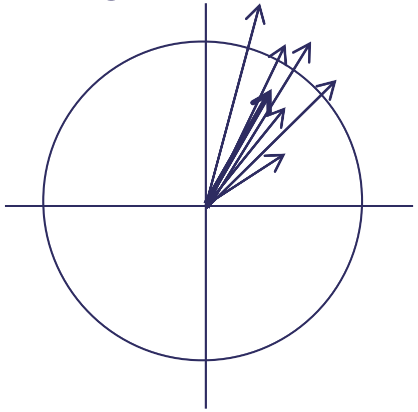
Phase-Locking vs Coherence

Low Coherence

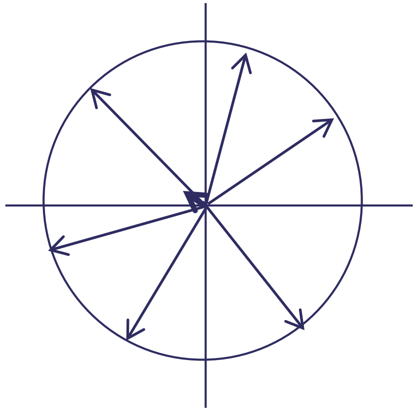


Every vector represents the amplitude and phase of one signal
(e.g. phase difference between two regions across trials).

High Coherence

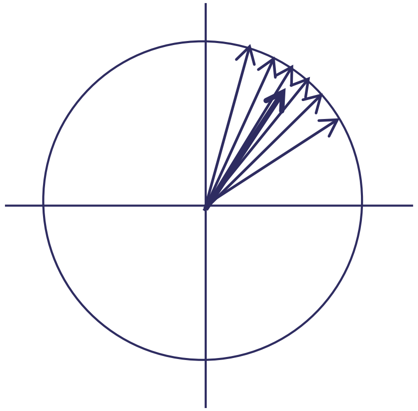


Low Phase-Locking



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).

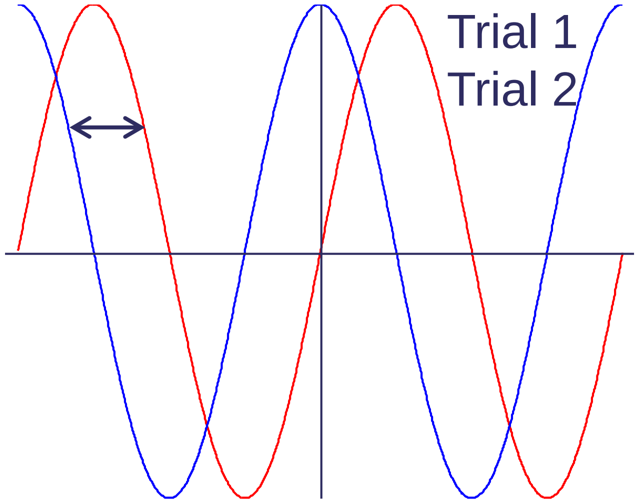
High Phase-Locking



Different Types of Phase-Locking

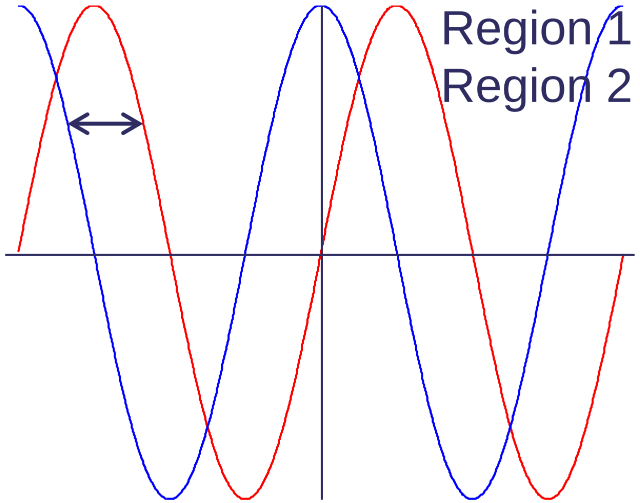
We ignore amplitudes, and are only interested in phase-relationships between two signal at a frequency f.

Inter-Trial Phase-Locking



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

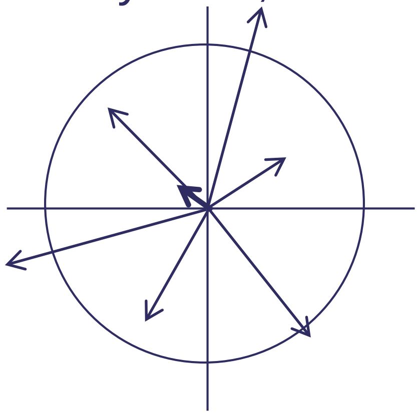
Inter-Regional Phase-Locking



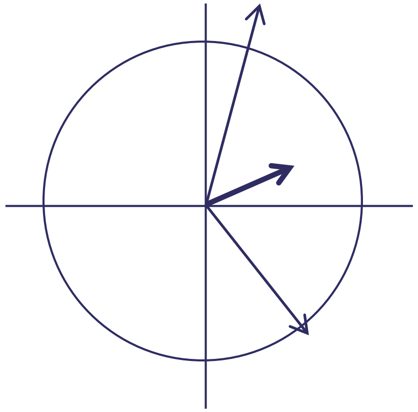
Does the phase difference between two regions at a particular frequency remain stable across trials with one region? (connectivity)

Sample Size / SNR Bias

Many trials, noise



Few trials, noise



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 effects is relatively small for ~>50 trials:

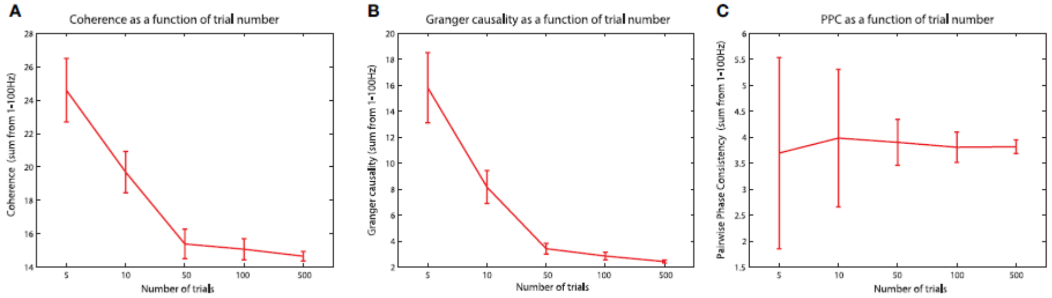
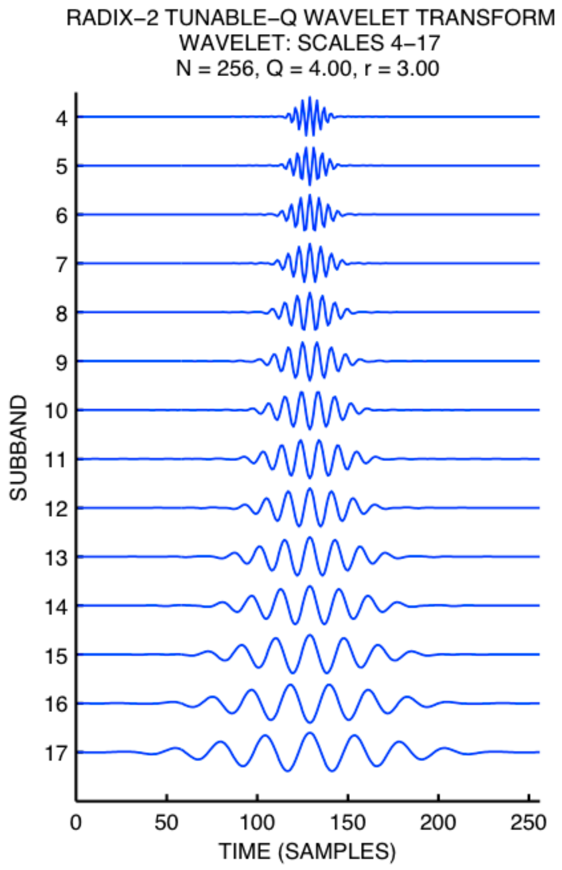


FIGURE 10 | Sample size bias for coherence and Granger causality estimates. (A–C) For each respective metric, simulations based on 5, 10, 50, 100, and 500 trials were run, and coherence **(A)**, Granger causality **(B)**, and PPC **(C)** were calculated. Each panel reflects the average ± 1 standard deviation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

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

Time-Resolved Connectivity

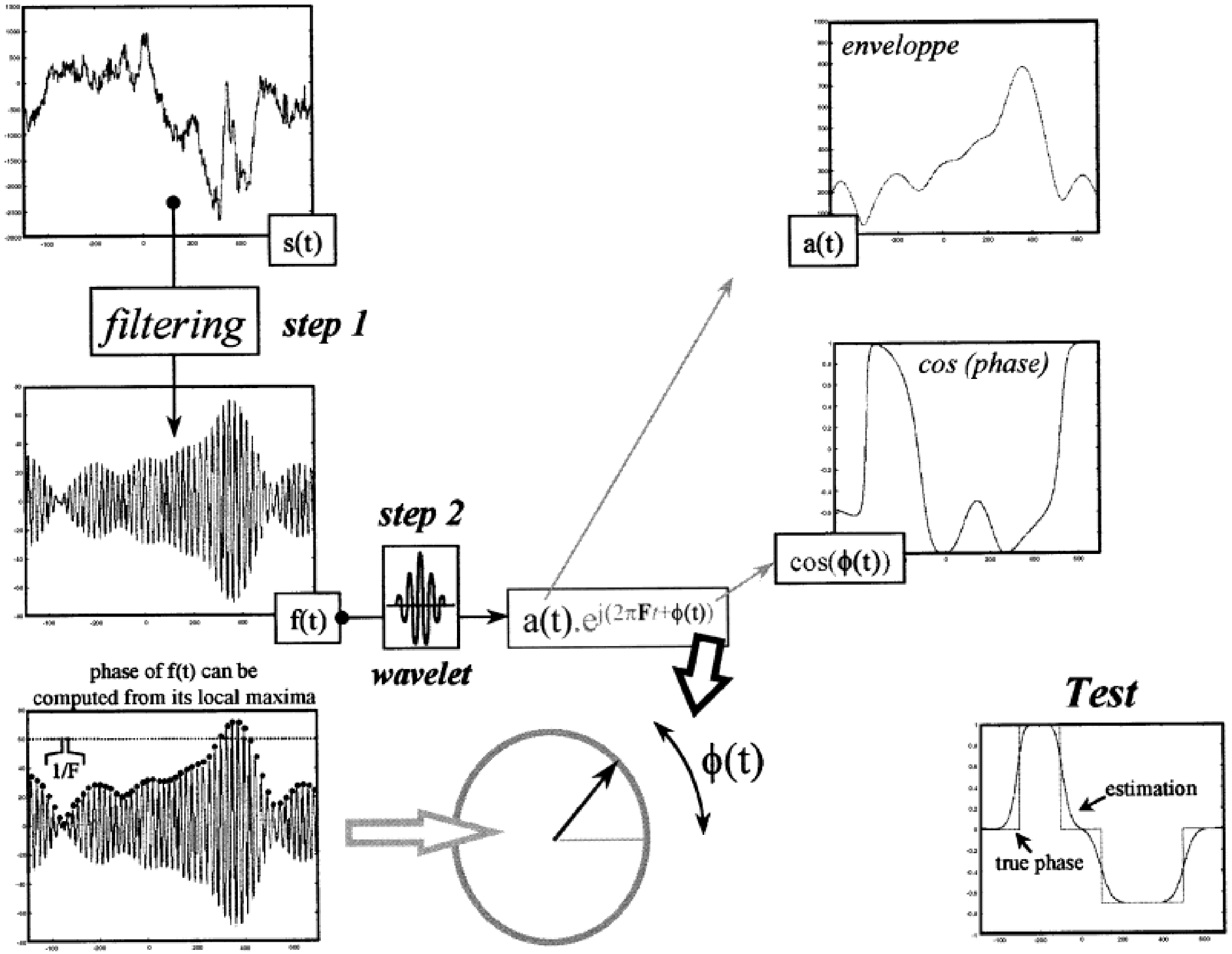
Spectral connectivity measures can be computed for separate time windows, or they can be computed continuously using wavelets or Hilbert transform (subject to general trade-off between frequency and time resolution)



Temporal resolution decreases as frequency decreases

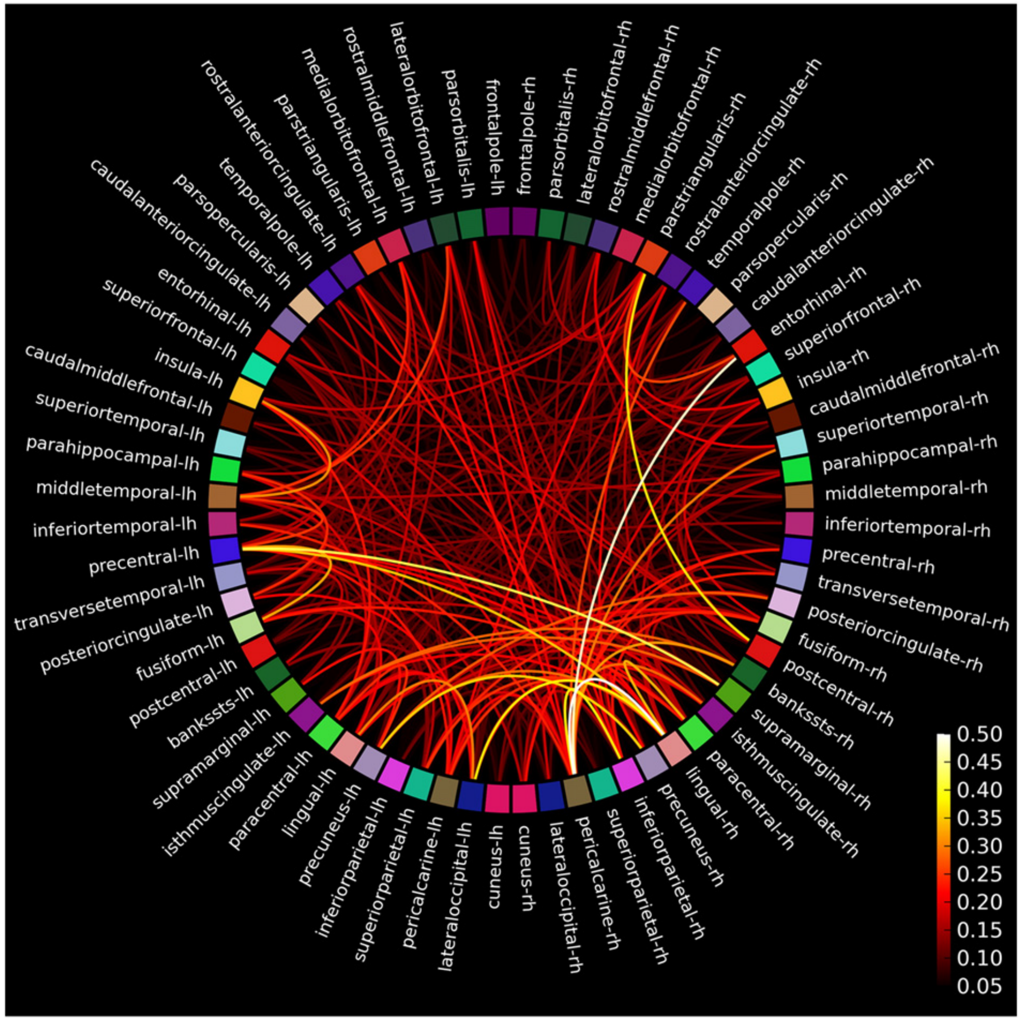
(wavelets are getting "broader")

Time-Resolved Connectivity



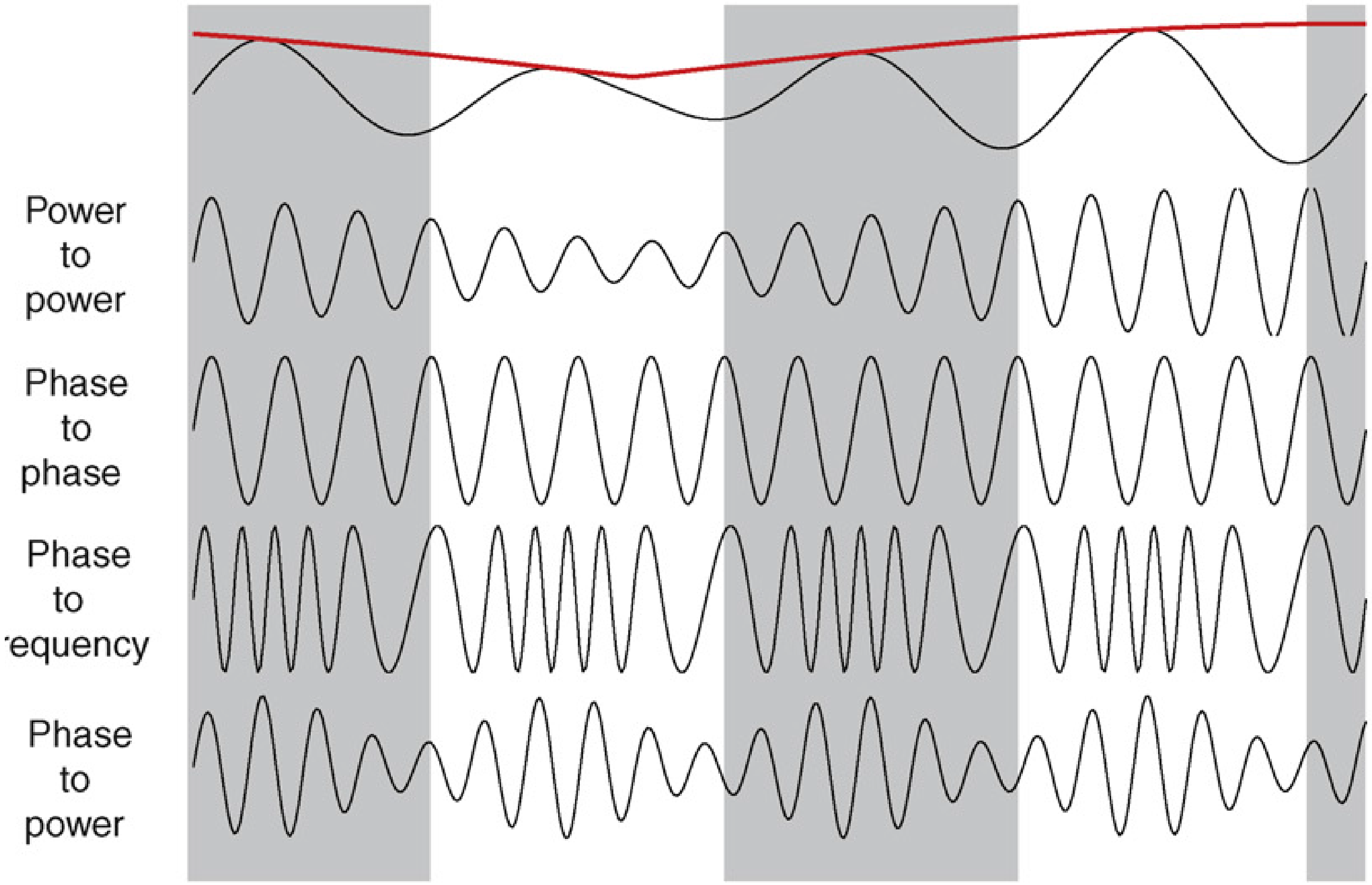
Lachaux et a., HBM 1999

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



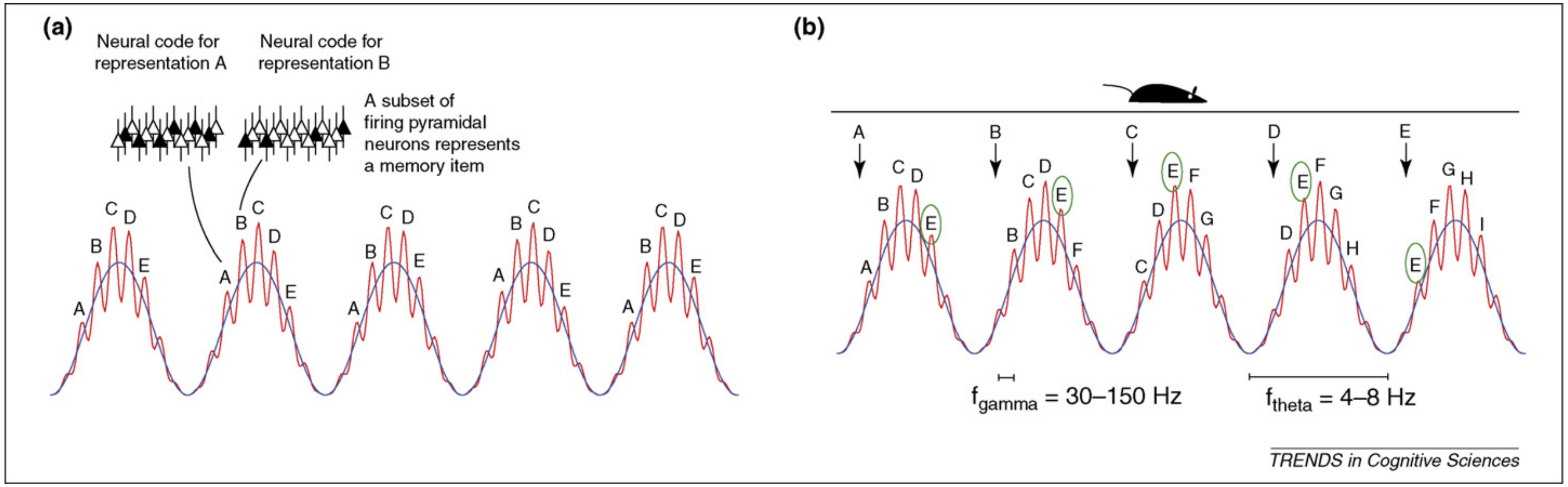
Gramfort et al., NI 2014
https://www.sciencedirect.com/science/article/pii/S1053811913010501

Cross-Frequency Coupling



Jensen & Colgin, TICS 2007

For Example: Theta-Gamma Coupling



Jensen & Colgin, TICS 2007

Figure 2. Models proposing computational roles for cross-frequency interactions between theta and gamma oscillations by means of phase coding. (a) In a model for working memory, individual memory representations are activated repeatedly in every theta cycle [10] (reviewed in Ref. [11]). Each memory representation is represented by a subset of neurons in the network firing synchronously. Because different representations are activated in different gamma cycles, the gamma rhythm serves to keep the individual memories segmented in time. The number of gamma cycles per theta cycle determines the span of the working memory. (b) A model accounting for theta phase precession in rats. As a rat advances through an environment, positional information is passed to the hippocampus. This activates the respective place cell representations, which provokes the prospective recall of upcoming positions. In each theta cycle, time-compressed sequences are recalled: one representation per gamma cycle. Consider the firing of a cell participating in representation E. As the rat advances, this cell fires earlier in the theta cycle, thus accounting for phase precession. According to this scheme, the number of gamma cycles per theta cycle is related quantitatively to the phase precession [13].

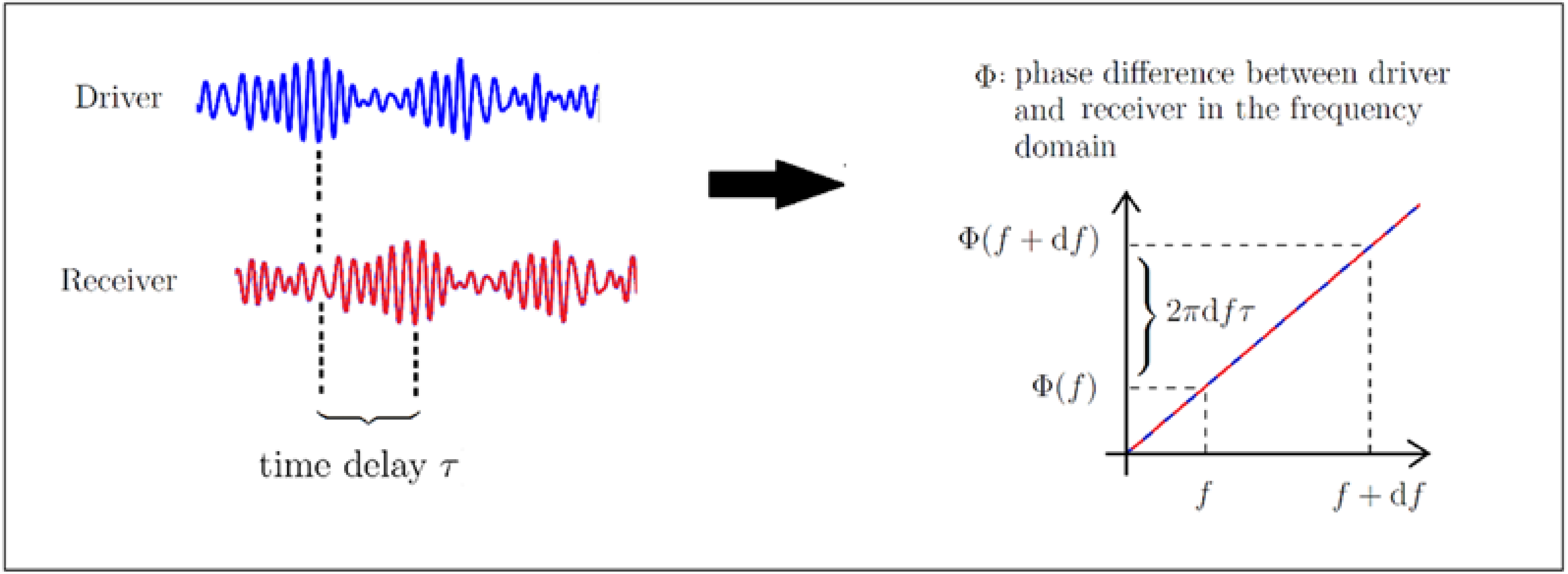
Directed Functional Connectivity

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/

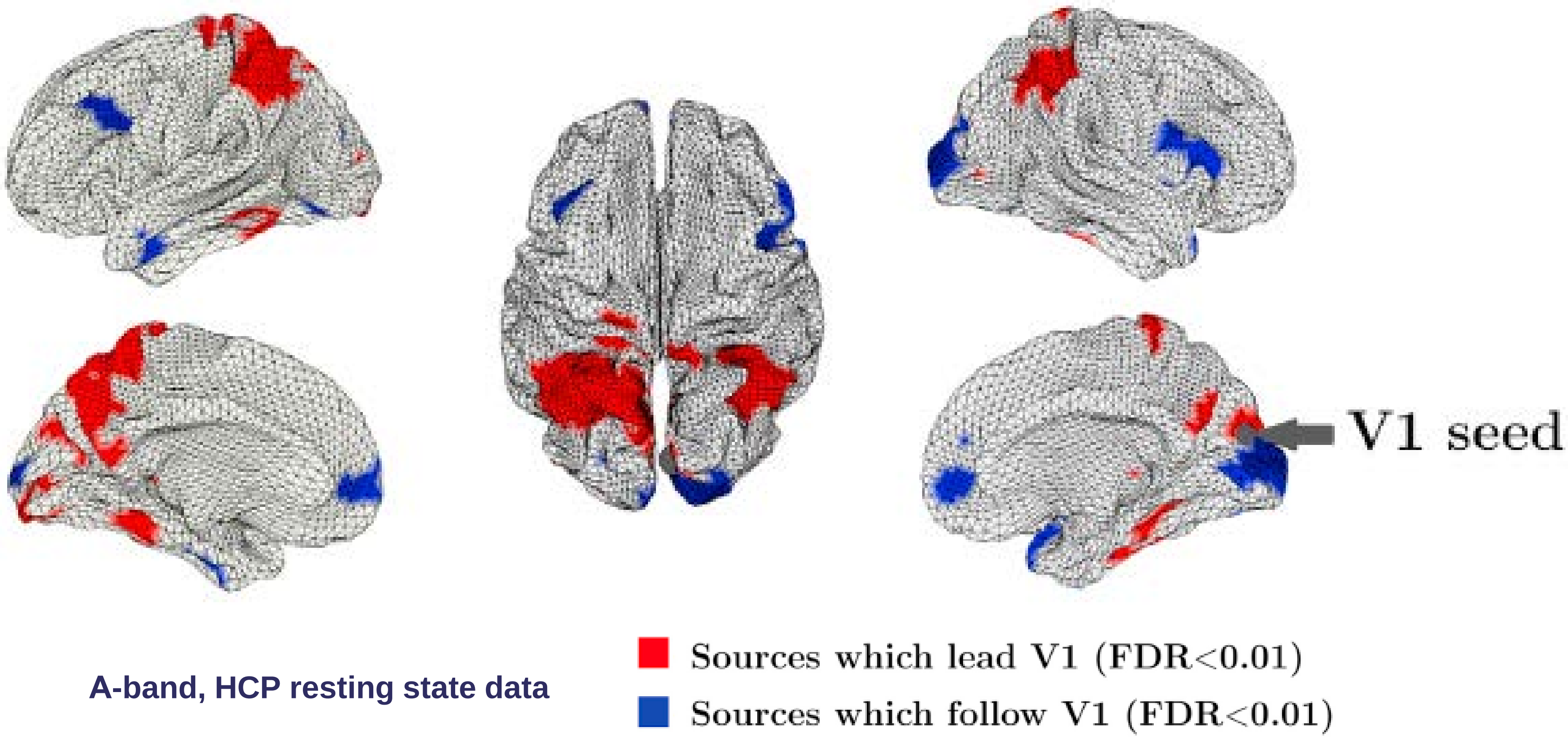
Basti et al., NI 2018, https://www.sciencedirect.com/science/article/pii/S1053811918301897



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

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