Connectivity analysis in MEG and EEG data: metrics and issues

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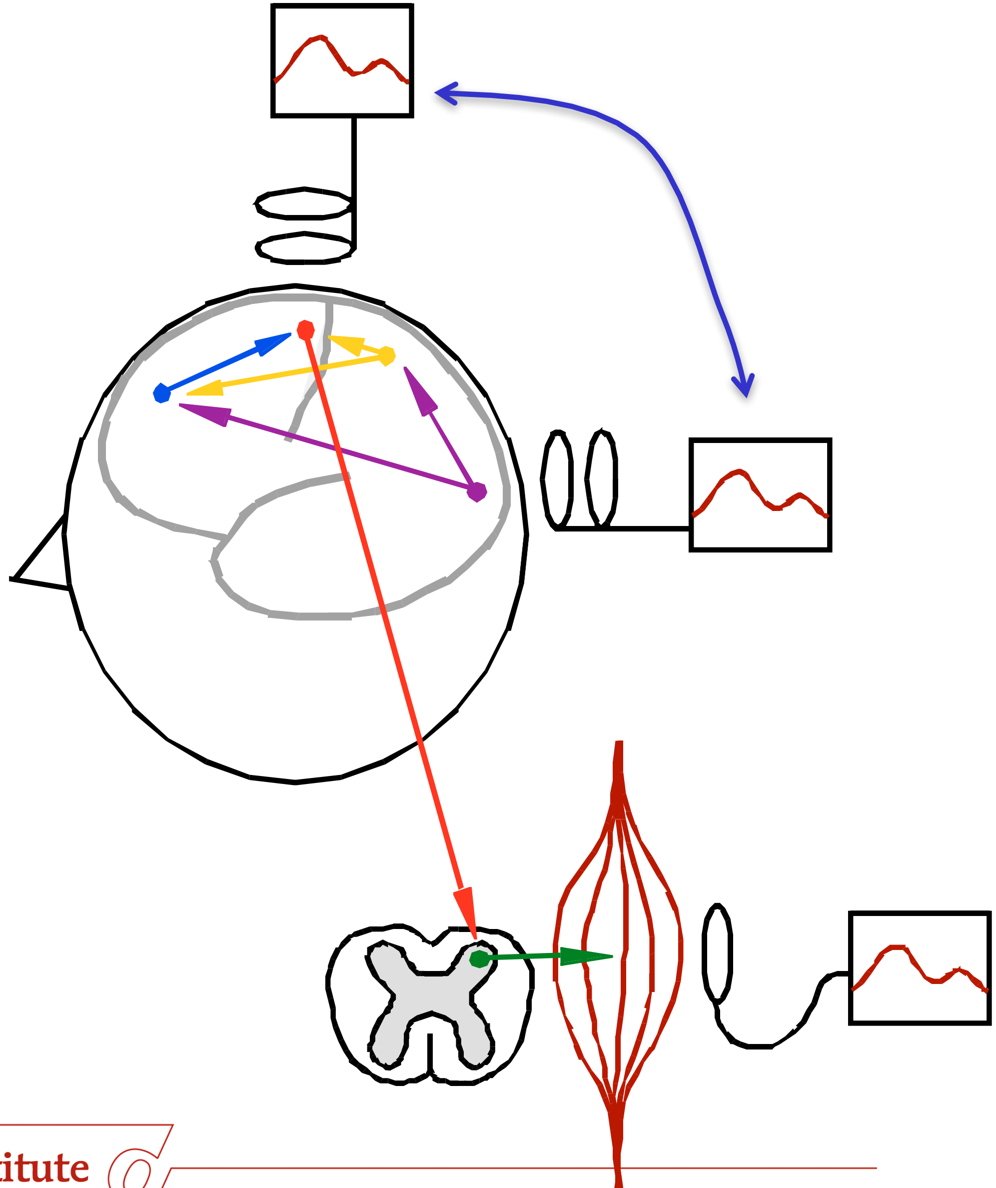
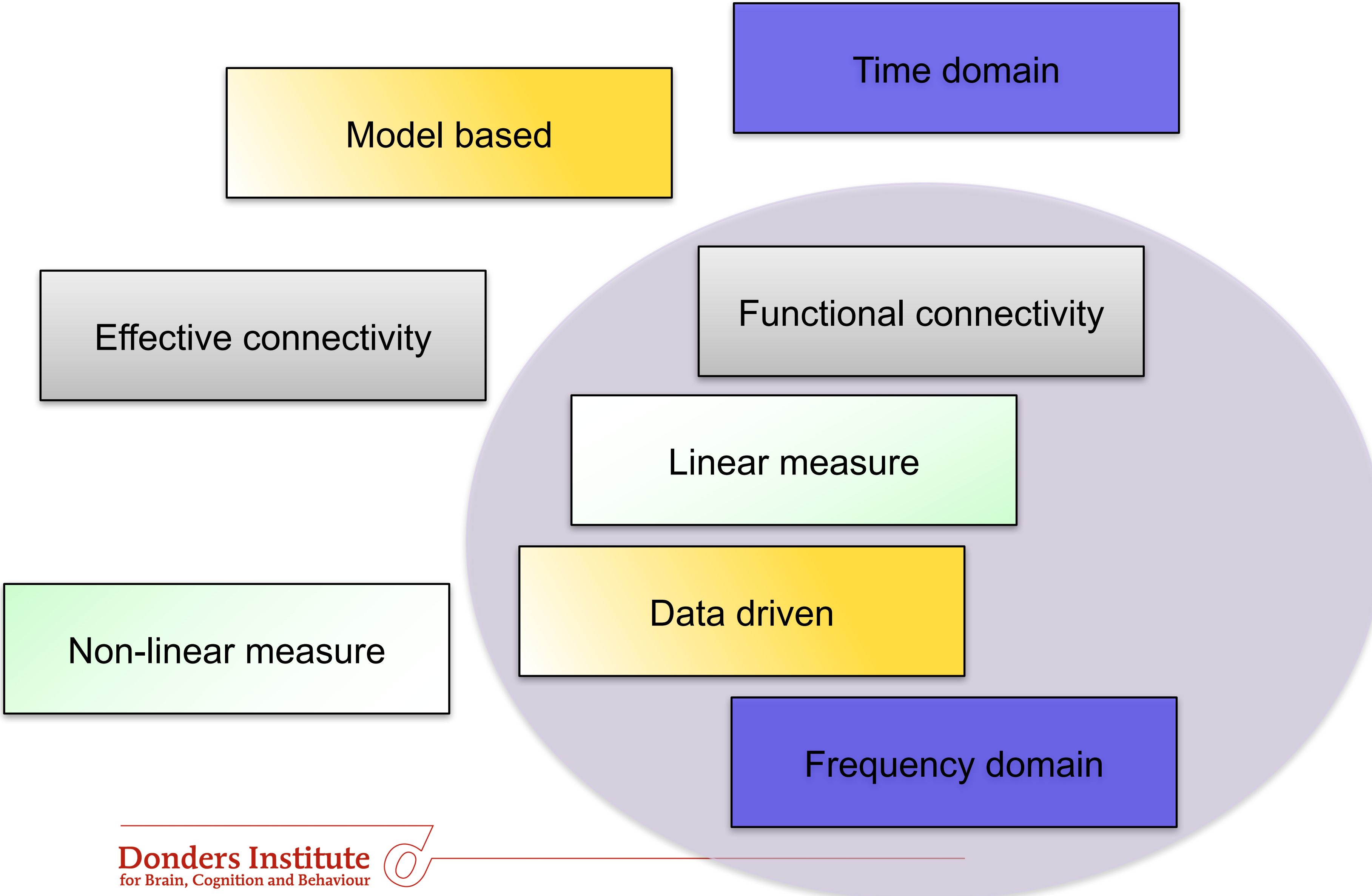
Connectivity analysis in MEG and EEG data: metrics …

Connectivity analysis: Beyond univariate analysis



Measures of connectivity



Measures of frequency domain connectivity

Coherence coefficient

Directed transfer function

Phase locking value

Phase lag index

Phase synchronization

Imaginary part of coherency

Partial directed coherence

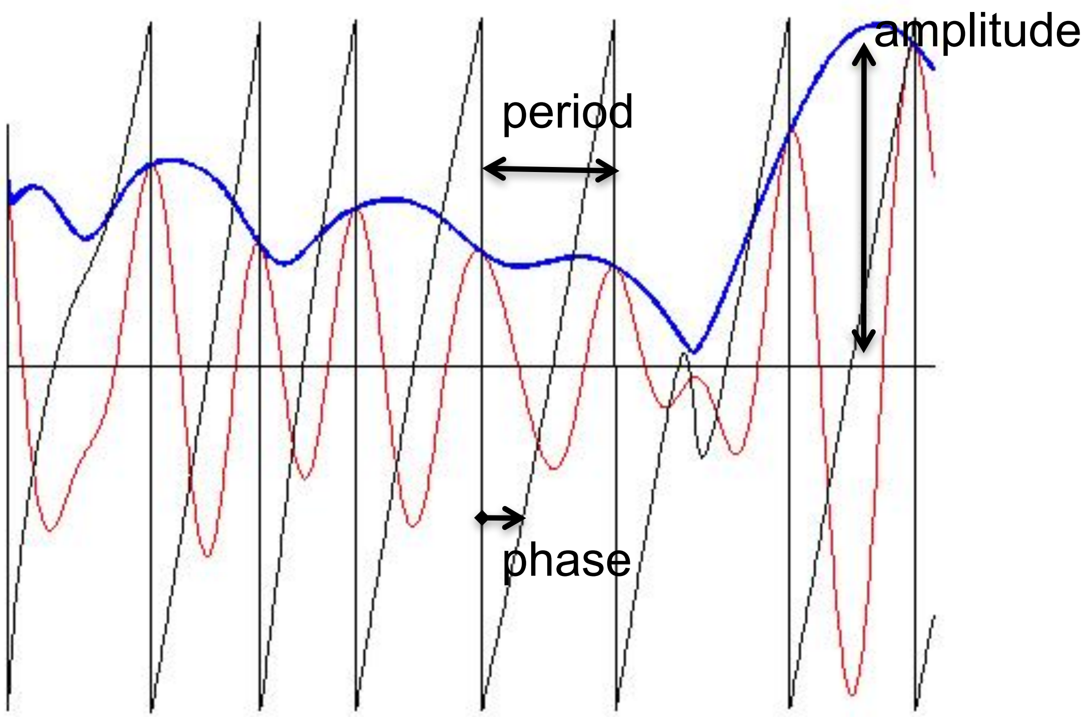
Pairwise phase consistency

Phase slope index

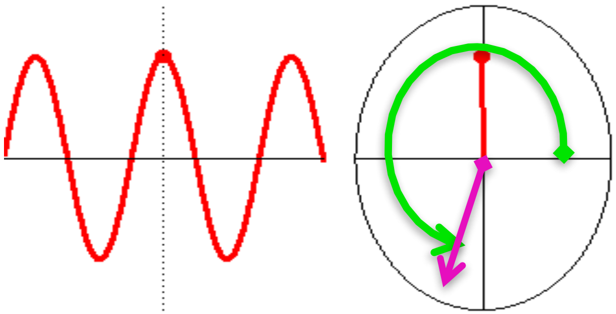
Synchronization likelihood

Frequency domain granger causality

What constitutes an oscillation? (recap)



What constitutes an oscillation? (the movie)



$= Ae^{i\varphi}$

What about 2 oscillations?
Let's look at the phase difference

phase signal 1

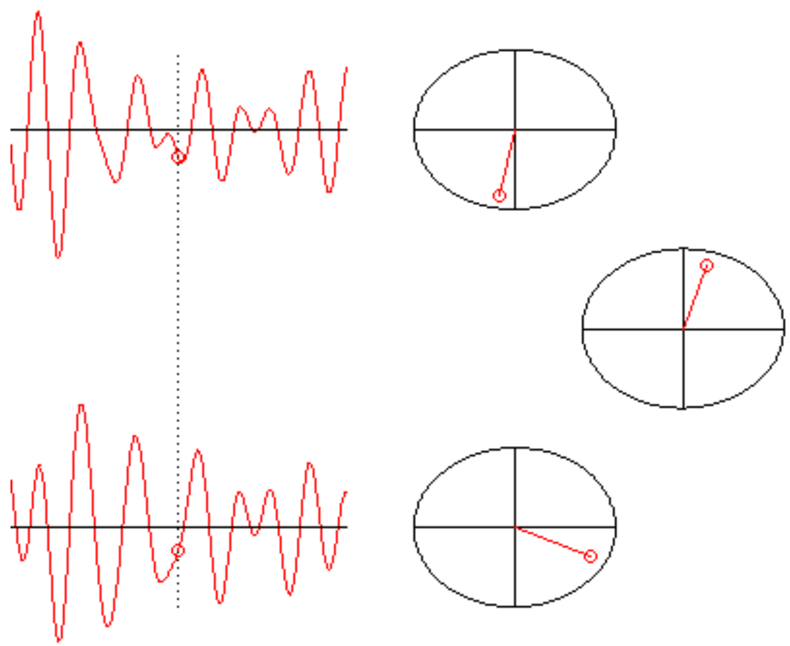
phase difference

phase signal 2

Phase difference is scattered:
Low synchrony

What about 2 oscillations?
Let’s look at the phase difference

$$x_1 = A_1 e^{i\varphi_1}$$



phase signal 1

phase difference

phase signal 2

$$x_2 = A_2 e^{i\varphi_2}$$

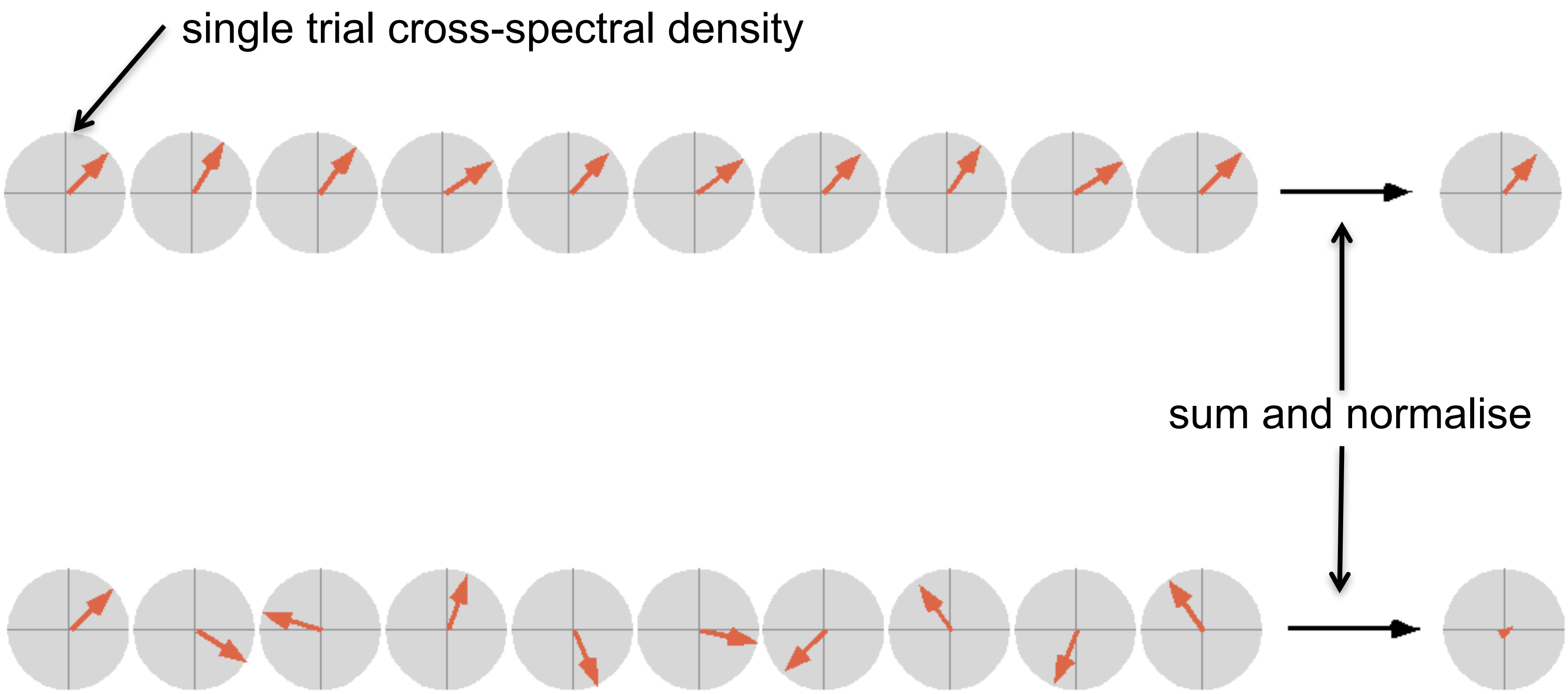
Phase difference is clustered:
High synchrony

$$x_1 x_2^* = \langle A_1 A_2 e^{i(\varphi_1 - \varphi_2)} \rangle$$

Measures of connectivity: coherence (the math view)

Coherence is computed from the *cross-spectral density*, which is obtained by *conjugate multiplication* of the frequency domain representation of the signals

$$x_1x_2^* = A_1e^{i\varphi_1} \times A_2e^{-i\varphi_2} = A_1A_2e^{i(\varphi_1-\varphi_2)}$$



Measures of connectivity: coherence & co

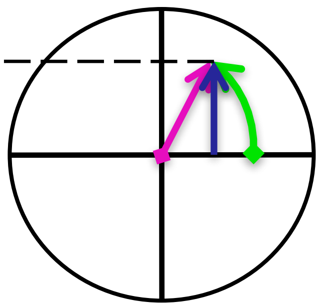
$$\text{Coherence} = \left| \frac{1/N\ \Sigma A_1 A_2 e^{i(\varphi_1-\varphi_2)}}{\sqrt{(1/N\ \Sigma A_1^{\,2})(1/N\ \Sigma A_2^{\,2})}} \right|$$

$$\text{PLV} = \left| \frac{1/N\ \Sigma 1 \text{x} 1 \text{x} e^{i(\varphi_1-\varphi_2)}}{\sqrt{(1/N\ \Sigma 1^2)(1/N\ \Sigma 1^2)}} \right| = \left| \frac{\Sigma e^{i(\varphi_1-\varphi_2)}}{N} \right|$$

Measures of connectivity: coherence & co

$$\text{Coherency} = \frac{1/N\ \Sigma A_1 A_2 e^{i(\varphi_1 - \varphi_2)}}{\sqrt{(1/N\ \Sigma {A_1}^2)(1/N\ \Sigma {A_2}^2)}} = Ce^{i\Delta\varphi}$$

Imaginary part of coherency



Linear prediction and directed interaction: the concept of Granger causality

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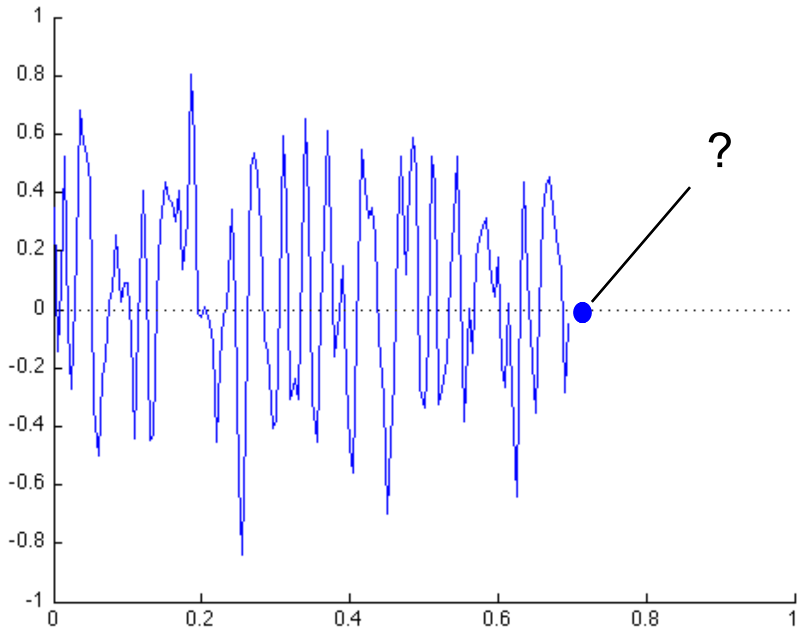
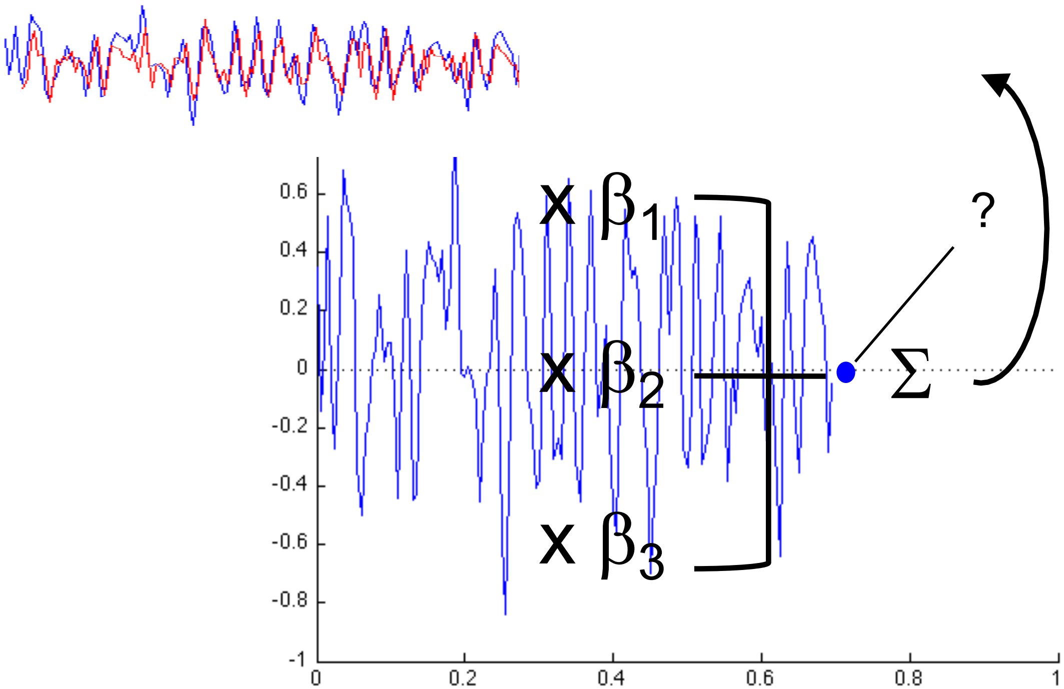


Linear prediction: autoregressive models



$$X(t) = \sum \beta_\tau X(t-\tau) + \eta$$

Two signals: bivariate autoregressive models

$$X(t) = \sum \beta_{\tau 1} X(t-\tau) + \eta_1$$

$$Y(t) = \sum \beta_{\tau 2} Y(t-\tau) + \eta_2$$

$$X(t) = \sum \beta_{\tau 11} X(t-\tau) + \sum \beta_{\tau 21} Y(t-\tau) + \varepsilon_1$$

$$Y(t) = \sum \beta_{\tau 12} X(t-\tau) + \sum \beta_{\tau 22} Y(t-\tau) + \varepsilon_2$$

Granger causality: compare the residuals

$$X(t) = \sum \beta_{\tau 1} X(t-\tau) + \eta_1$$

$$Y(t) = \sum \beta_{\tau 2} Y(t-\tau) + \eta_2$$

$$X(t) = \sum \beta_{\tau 11} X(t-\tau) + \sum \beta_{\tau 21} Y(t-\tau) + \varepsilon_1$$

$$Y(t) = \sum \beta_{\tau 12} X(t-\tau) + \sum \beta_{\tau 22} Y(t-\tau) + \varepsilon_2$$

$$F_{Y \to X} = \ln\left(\frac{\mathrm{var}(\eta_1)}{\mathrm{var}(\varepsilon_1)}\right)$$

$$F_{X \to Y} = \ln\left(\frac{\mathrm{var}(\eta_2)}{\mathrm{var}(\varepsilon_2)}\right)$$

Analogy between Granger and ‘plain’ regression

$$X(t) = \sum \beta_{\tau 1} X(t-\tau) + \eta_1$$

$$Y(t) = \sum \beta_{\tau 2} Y(t-\tau) + \eta_2$$

$$X(t) = \sum \beta_{\tau 11} X(t-\tau) + \sum \beta_{\tau 21} Y(t-\tau) + \varepsilon_1$$

$$Y(t) = \sum \beta_{\tau 12} X(t-\tau) + \sum \beta_{\tau 22} Y(t-\tau) + \varepsilon_2$$

$$\text{data} = \sum \beta_\kappa X_\kappa + \eta$$

$$\text{data} = \sum \beta'_\kappa X_\kappa + \beta'_{\kappa+1} X_{\kappa+1} + \varepsilon$$

$$F_{Y \to X} = \ln\left(\frac{\mathrm{var}(\eta_1)}{\mathrm{var}(\varepsilon_1)} \right)$$

$$F \sim \frac{\mathrm{var}(\eta)}{\mathrm{var}(\varepsilon)}$$

…only the inference is different

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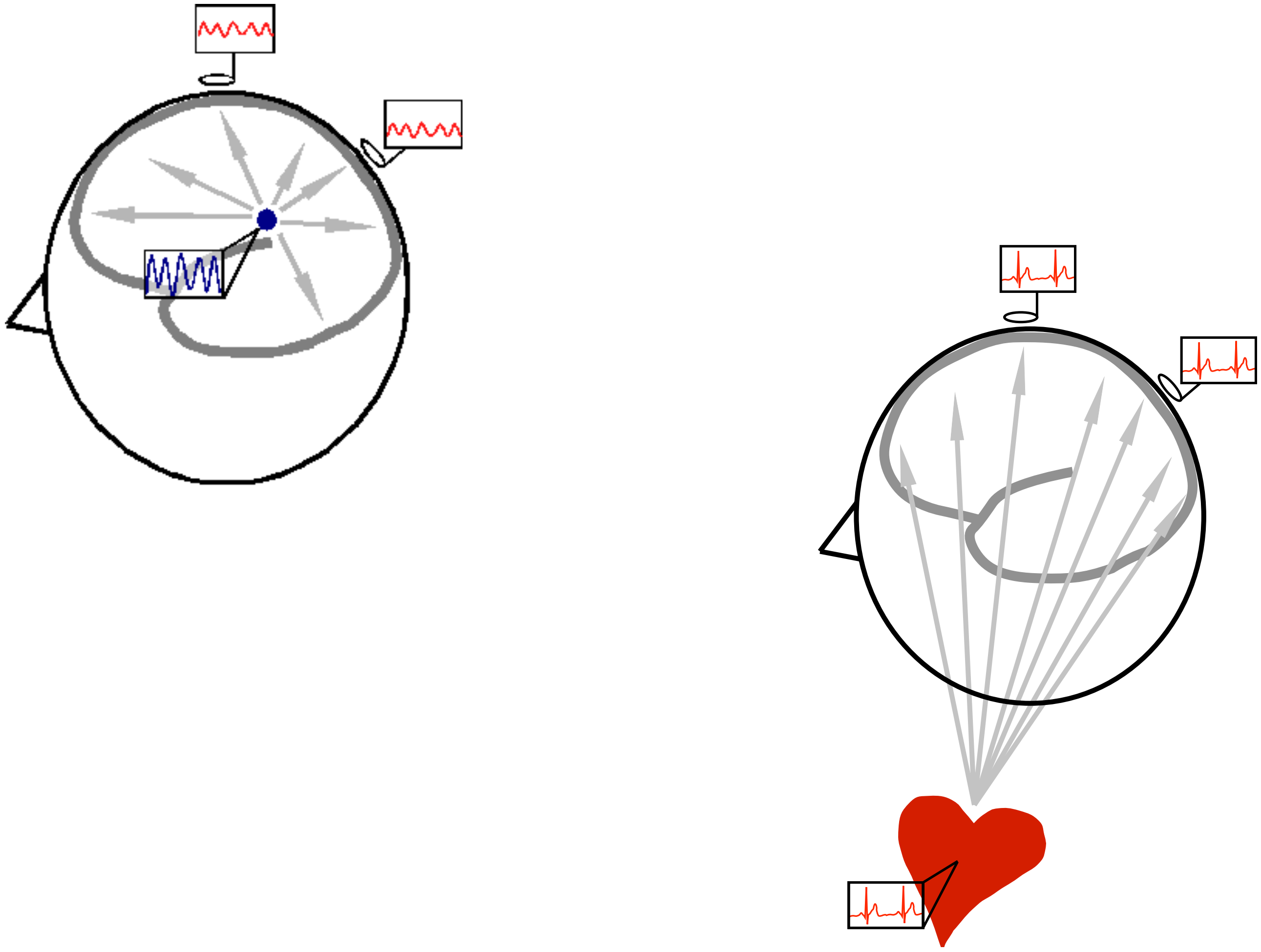
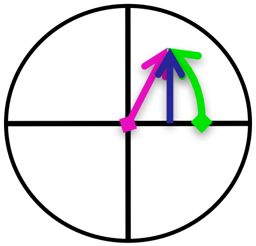
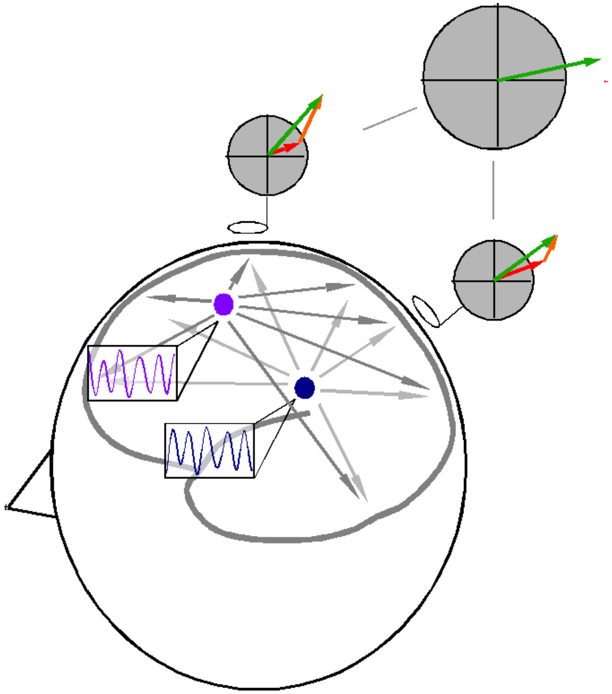
Practial issues: Electromagnetic field spread



Practical issues: imaginary part of coherency

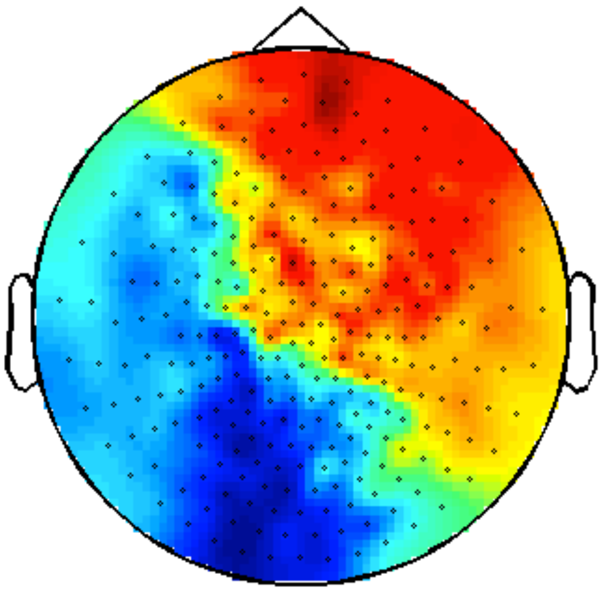


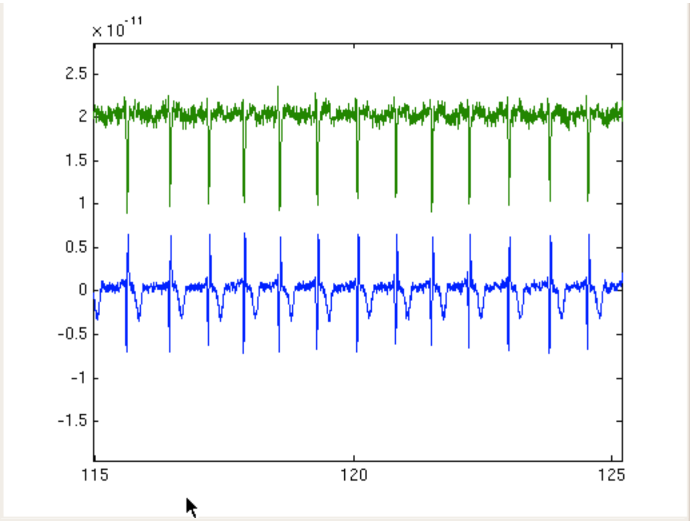


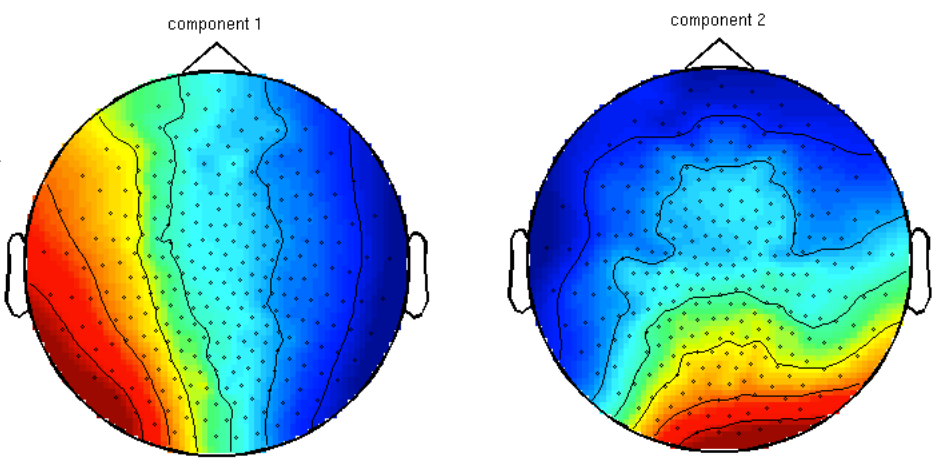
Im(coherency) $\neq$ **0**

MEG connectivity

WPLI suggests fronto-occipital directed interaction (alpha band)







Confounds for connectivity

- Common pick up
- - other sources in the brain
- - other physiological sources
- - especially problematic if those sources have some "internal synchronization" themselves

- Differences in signal (or noise) between experimental conditions
- - better SNR -> more reliable estimate of the phase
- - more reliable phase -> more consistent phase difference

Concluding remarks

- Connectivity analysis is really informative
- Many measures on the market
- Interpretation of results should be done with care

Measures of connectivity: coherence & co

$$\text{Coherency} = \frac{1/N\ \Sigma A_1 A_2 e^{i(\varphi_1 - \varphi_2)}}{\sqrt{(1/N\ \Sigma A_1^2)(1/N\ \Sigma A_2^2)}} = Ce^{i\Delta\varphi}$$

Slope of relative phase spectrum indicates time delay