Brain Rhythmic Activity and Imaging Dynamic Networks: From Coactivation to Causality

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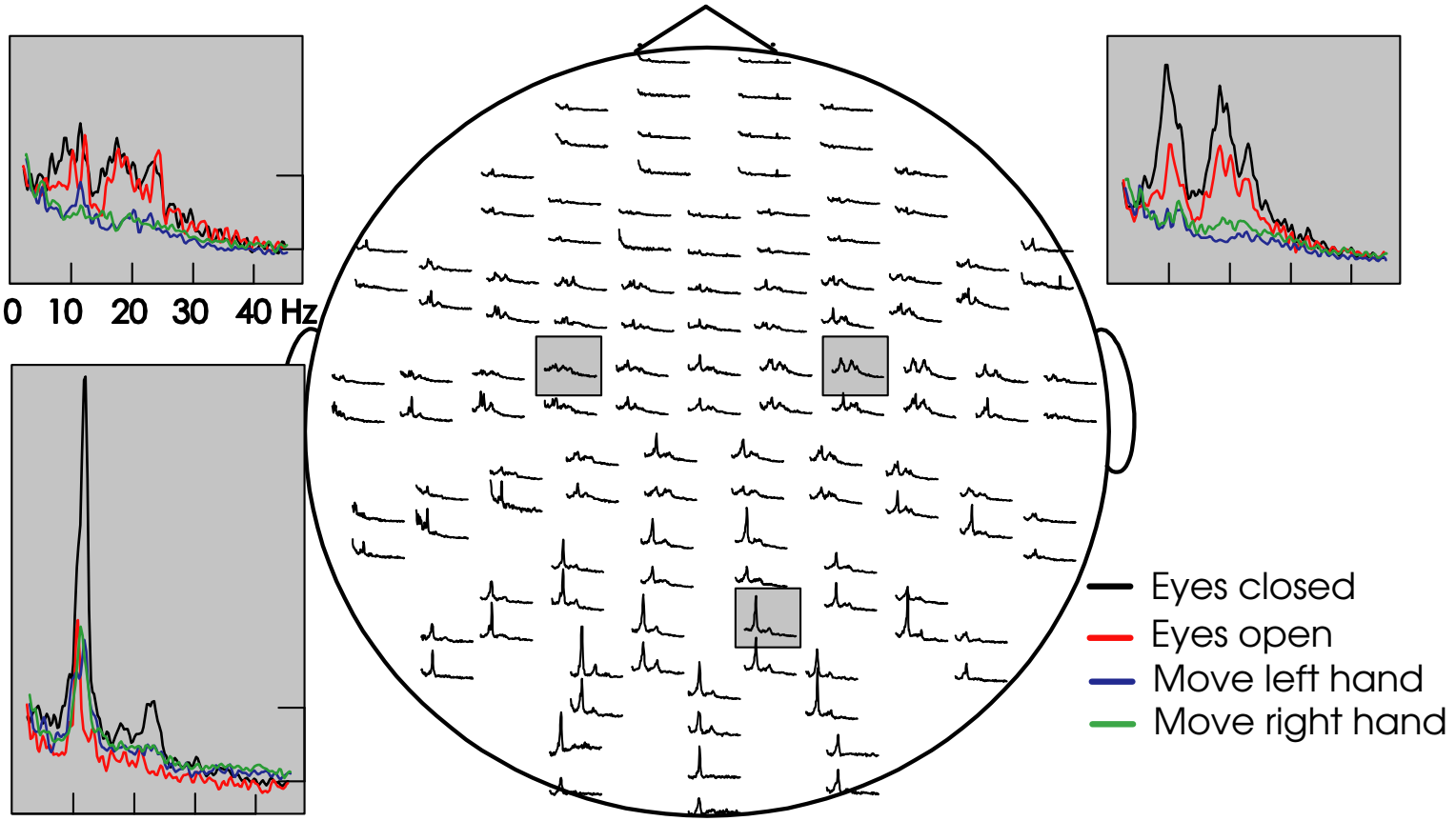
Outline

- Rhythmic activity in the brain
- Rhythmic interactions
- Cortical level analysis of rhythmic activity and interactions with Dynamic Imaging of Coherent Sources (DICS)

Spontaneous oscillations

- Multiple generators in different locations
  - posterior α (8-13 Hz), rolandic μ (7-13, 16-24 Hz), frontal θ (3-8 Hz), somatomotor β (13-30 Hz)
- Level of activity affected, e.g., by state of arousal

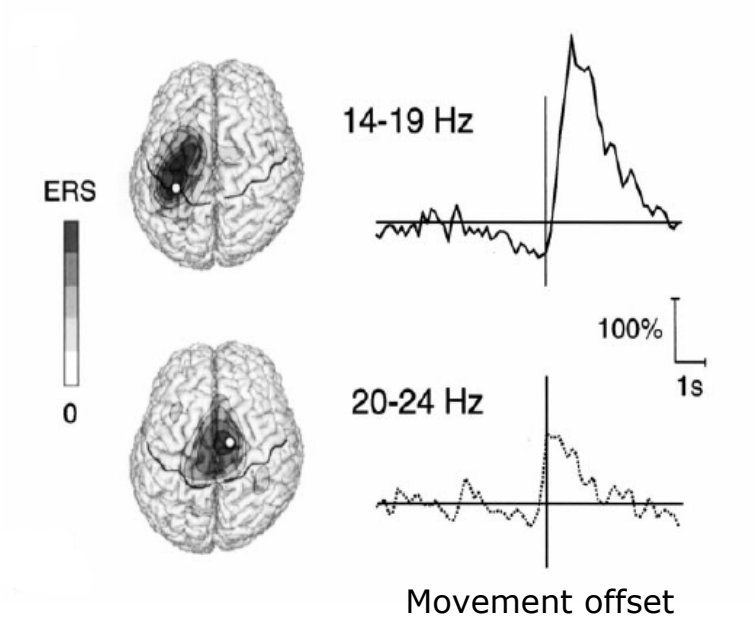
Spectral modulation



Salmelin & Hari EEG J 1994
Hari & Salmelin TINS 1997

Modulation of rhythmic activity

- Stimuli and tasks can transiently modulate level of rhythmic activity
  - Both suppression and enhancement



Pfurtscheller Neurosci Lett 2000

Rhythmic interactions

- Synchrony over multiple frequency bands most likely mechanism of large-scale integration *(Varela et al Nat Rev Neurosci 2001)*
- Both coactivation and causality measures used for quantification

Coactivation measures

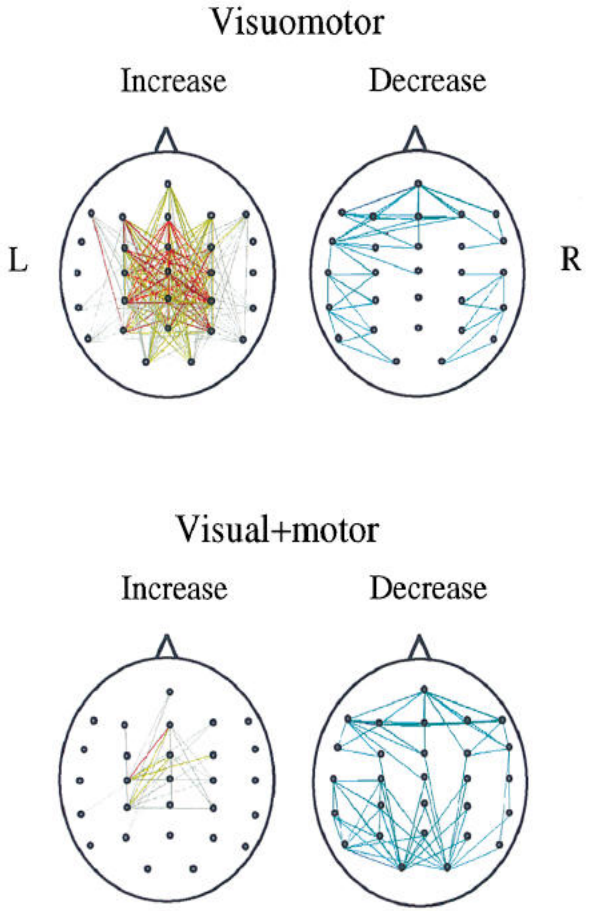
- Coherence: cross-spectral density normalized with power spectral densities
  - Co-occurrence of oscillations, amplitude dependent
- Phase locking (PLV/PLS): estimation of phase difference constancy in event-related paradigms
- Synchronization index (SI): estimation of preferred phase difference
  - Applicable also in continuous tasks

Causality measures

- Directionality index (DI): estimation of uni- versus bi-directionality from instantaneous phases
- Granger causality: quantification of predictability of one time series using information contained in another series, based on autoregressive models
  - Also frequency domain extension
  - Related measures: Directed transfer function (DTF), Partial directed coherence (PDC)

Functional coupling (coactivation)

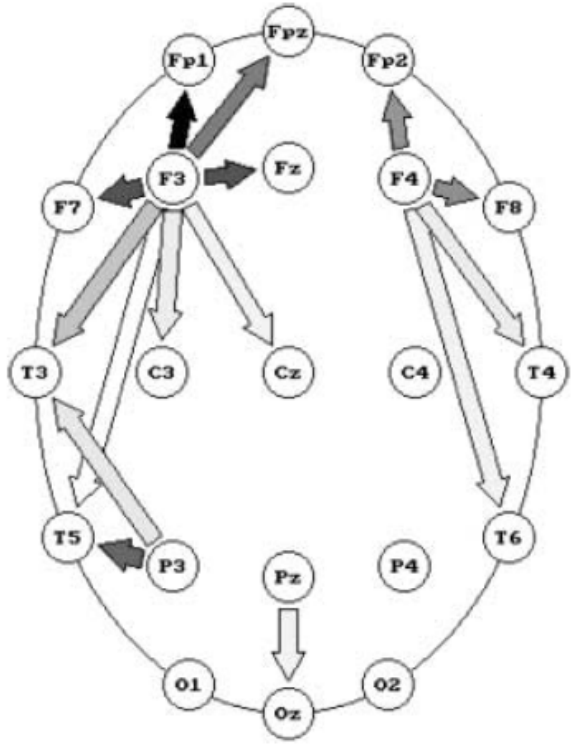
- Changes in coherence and/or phase coupling between tasks
  - typically at the EEG/MEG sensor level



Classen et al J Neurophysiol 1998

Effective coupling (causality)

- Directed influence between pre-defined sets of areas (or at the sensor level)
  - Prediction of one time series based on information contained in another



Kaminski et al Biol Cybern 2001

Imaging dynamic networks

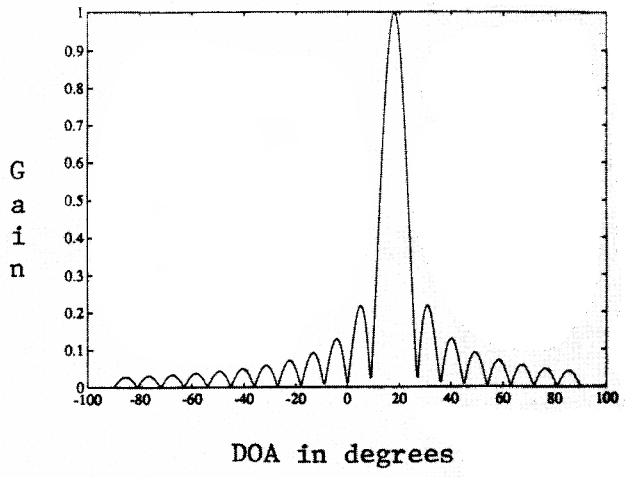
- Cortical level imaging done mostly
  - For predefined regions of interest *(Astolfi et al Clin Neurophysiol 2005, Babiloni et al Neuroimage 2005)*
  - By localizing areas via activity measures
    - Localization based on evoked responses *(Ioannides et al Hum Brain Mapp 2000)*
    - Localization of areas active at tag-frequecy *(David et al Neuroimage 2003, Cosmelli et al Neuroimage 2004)*
- Imaging possible also via cortico-cortical mapping of coherence
  - Beamforming *(Gross et al PNAS 2001)*
  - Minimum norm estimates *(Jerbi et al PNAS 2007)*

Dynamic Imaging of Coherent Sources (DICS)

- Direct localization of interacting networks at cortical level
  - Imaging of oscillatory power and coherence in continuous tasks
    - natural tasks
  - Imaging of coherence
    - between cortical areas
    - between external signals and cortical areas
  - Estimation of time-courses of activity for phase-coupling/causality analysis

DISC: Frequency domain beamforming

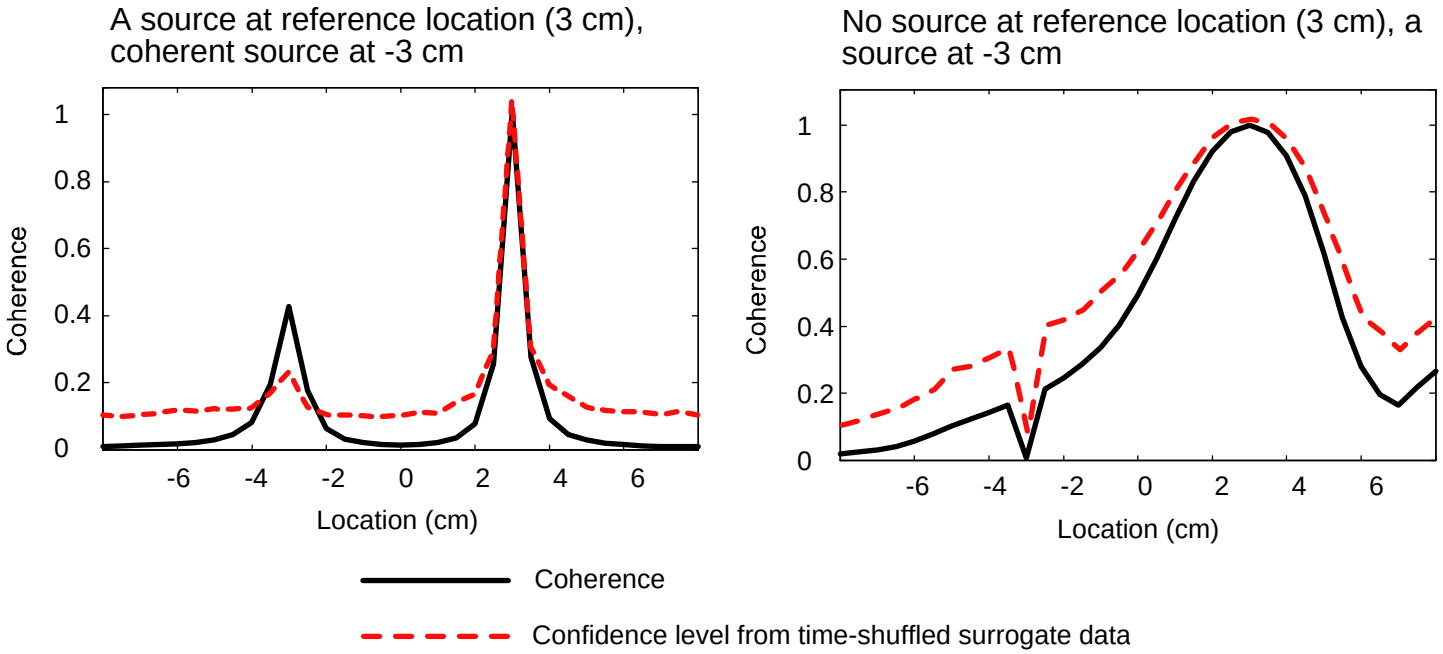
- Linearly weighted sensor-level data used to estimate "activity" at cortical level
  - Sensor-level data represented by cross-spectral density matrix
  - Cortical level signals not independent, possible leakage between spatial filters



Van Veen and Buckley IEEE ASSP Magazine 1988

Significance of coupling

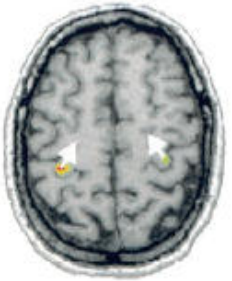
- Testing via surrogate data
  - Random shuffling: if time-series properties are identical (leakage), correlation remains



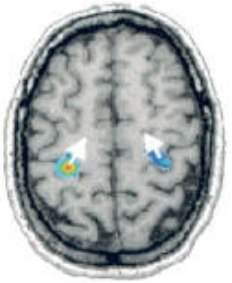
What DICS yields?

- Noise normalized power maps
- Coherence maps from a reference area to all other locations in the brain

Simulated sources



Rhythmic activity

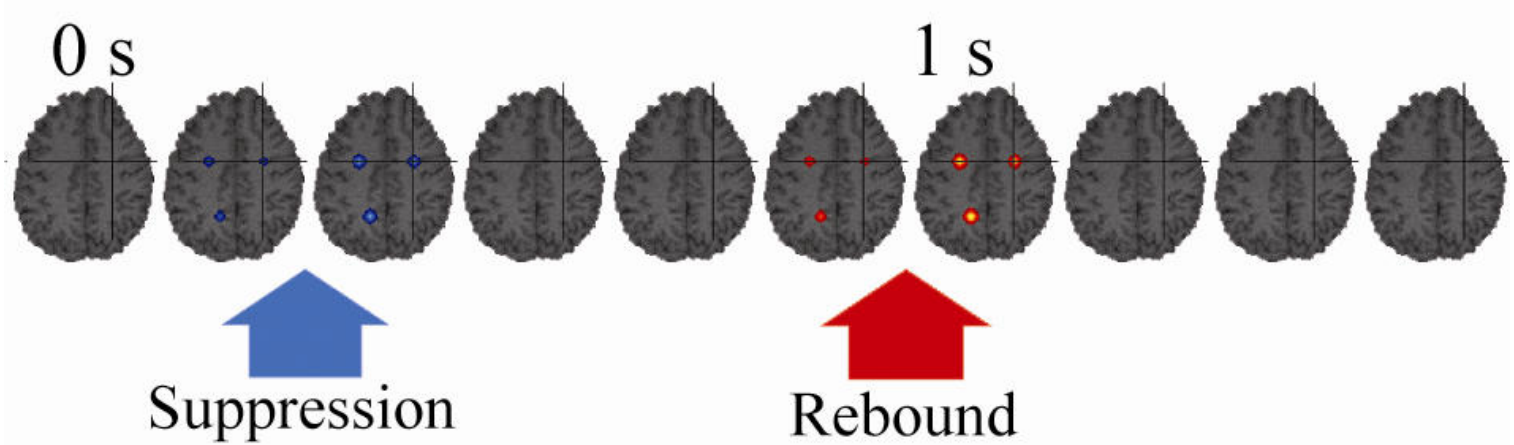


Cortico-cortical coherence

Gross et al PNAS 2001

event-related DICS (erDICS)

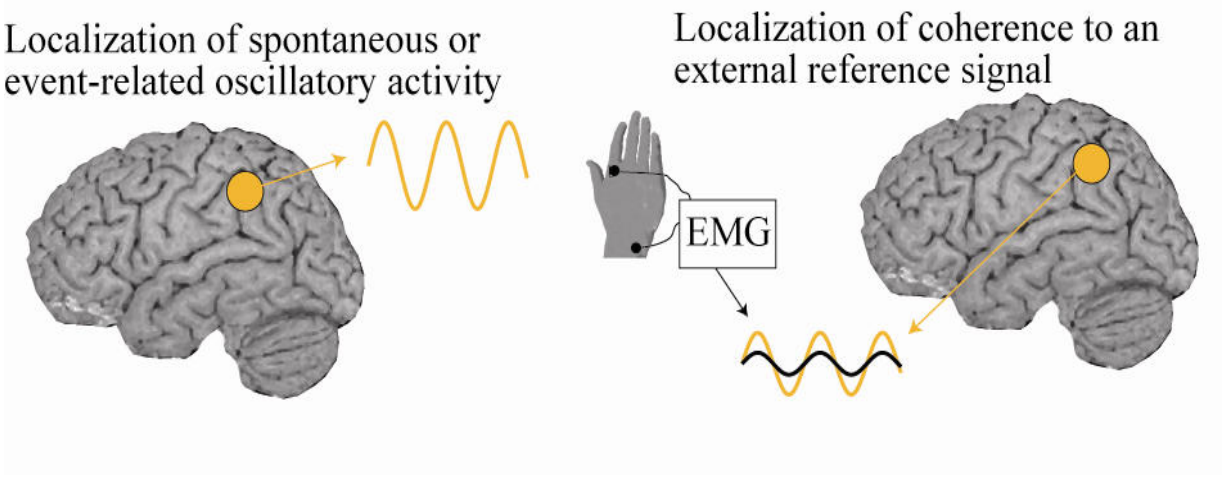
- Mapping of event-related modulation of rhythmic activity
  - Cross spectral density matrix as a function of time (wavelets)
    - Can be extended to coherence imaging



Laaksonen et al Neuroimage in press

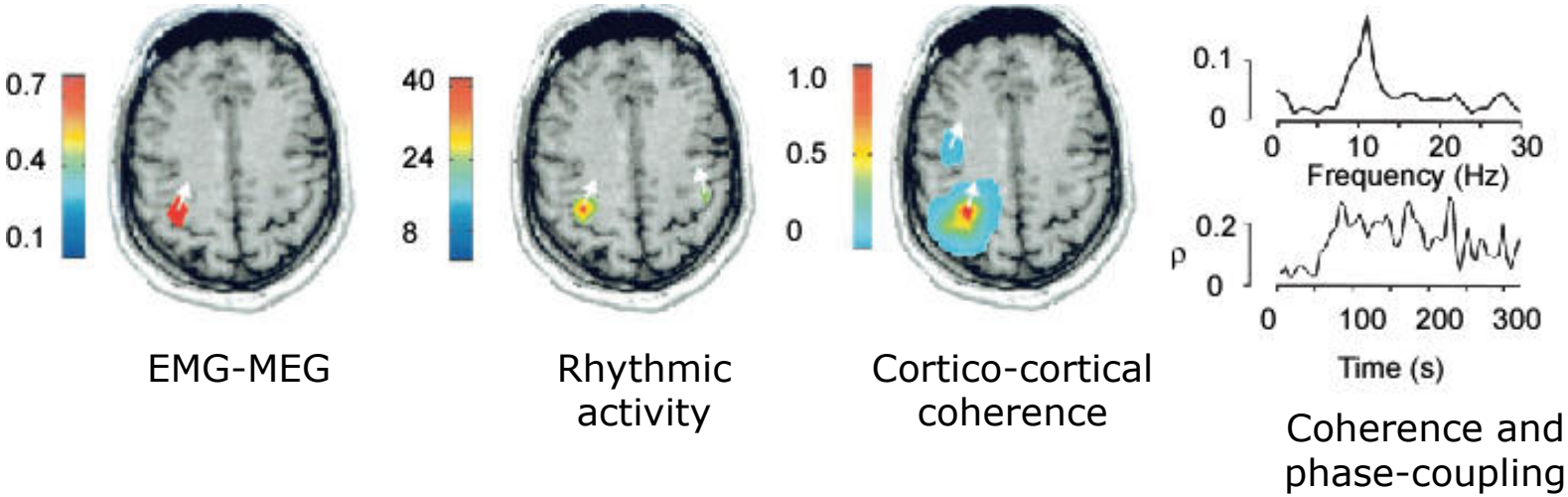
Identification of cortical reference areas

- Cortical reference area required for cortico-cortical imaging of coherence
- Identifiable via
  - External reference signals
  - Rhythmic activity



Rhythmic interactions during Parkinsonian tremor

- Cortical reference via oscillatory power and EMG-MEG coherence
- Increased phase-coupling (SI) between M1 and PMC during tremor



EMG-MEG

Rhythmic activity

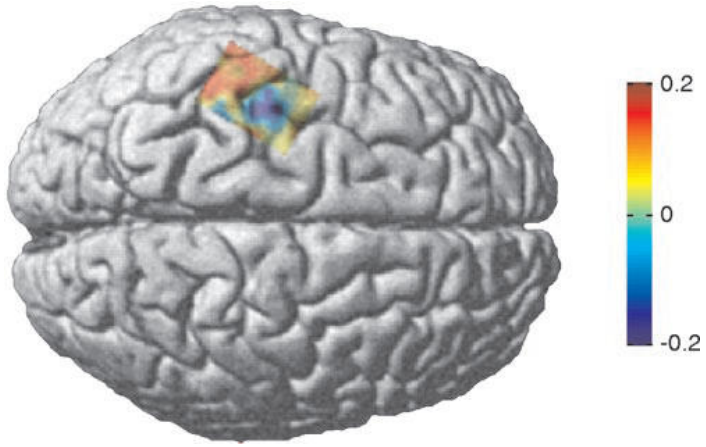
Cortico-cortical coherence

Coherence and phase-coupling

Gross et al PNAS 2001

Interactions during finger movement

- Right index finger movement task
- Contralateral M1 coherent with EMG-signal
- Separation of M1/S1 with directionality index (DI)

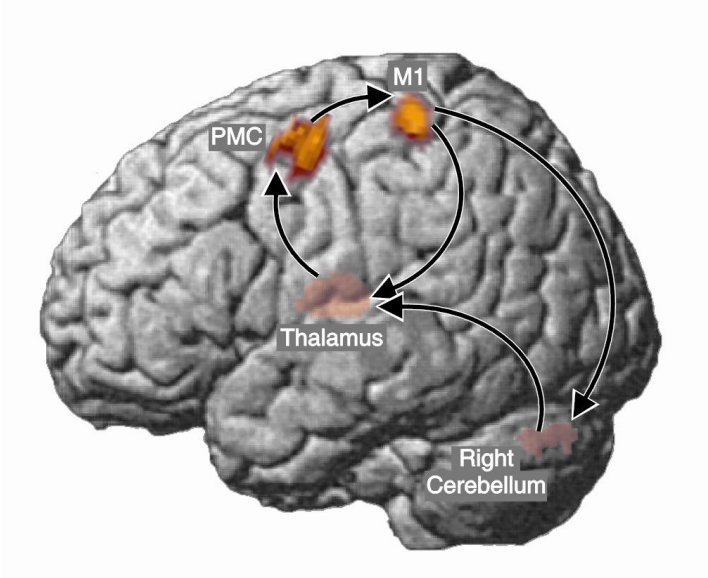


Separation of efferent and afferent components

Gross et al PNAS 2002

Imaging of networks from M1

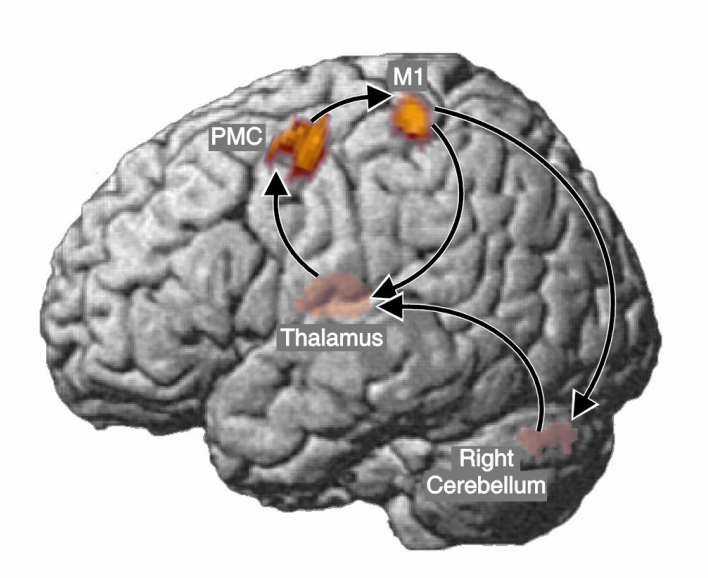
- Cortico-cortical coherence between M1 and all other brain regions
  - Group analysis in SPM
- Connectivity characterization with phase-coupling (SI) and causal measures (DI)



Gross et al PNAS 2002

Imaging of networks from M1

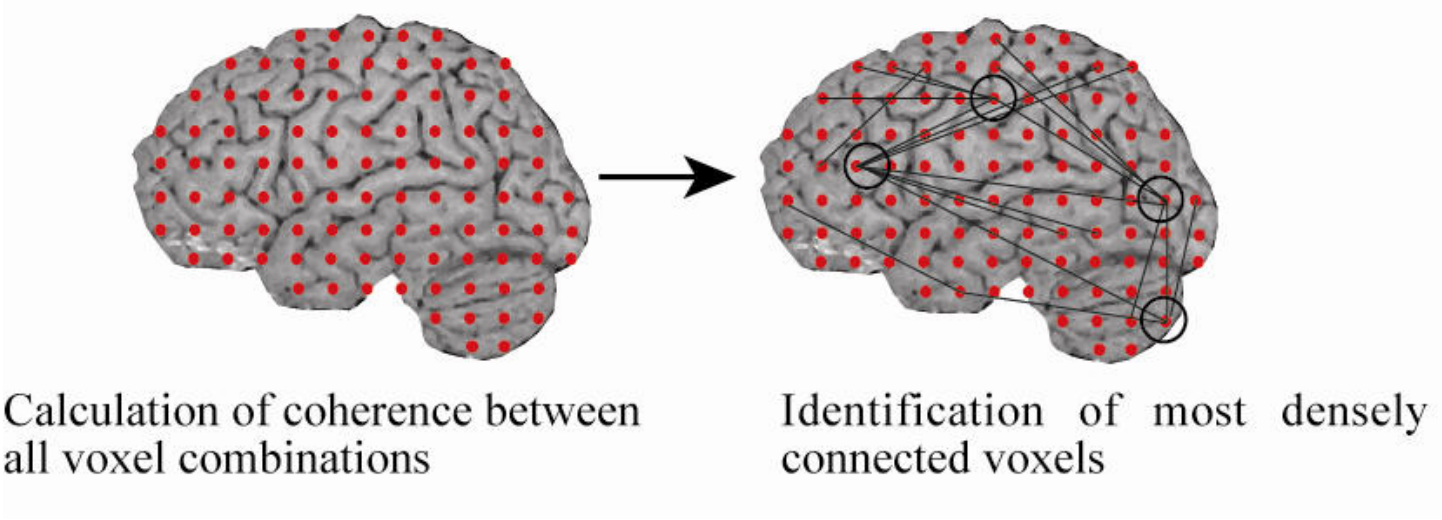
- Cortico-cortical coherence between M1 and all other brain regions
  - Group analysis in SPM2
- Connectivity characterization with phase-coupling (SI) and causal measures (DI)



Butz et al J Physiol Paris 2006, Pollok et al Exp Brain Res 2006, J Cogn Neurosci 2007

Localization of reference areas with cortico-cortical coherence

- Meaningful external reference signals not readily available in cognitive tasks
- Oscillatory power may not reveal most relevant areas
- Connection density estimation (CDE)
  - Coherence between all voxel combinations
  - Counting the amount of connections for each voxel



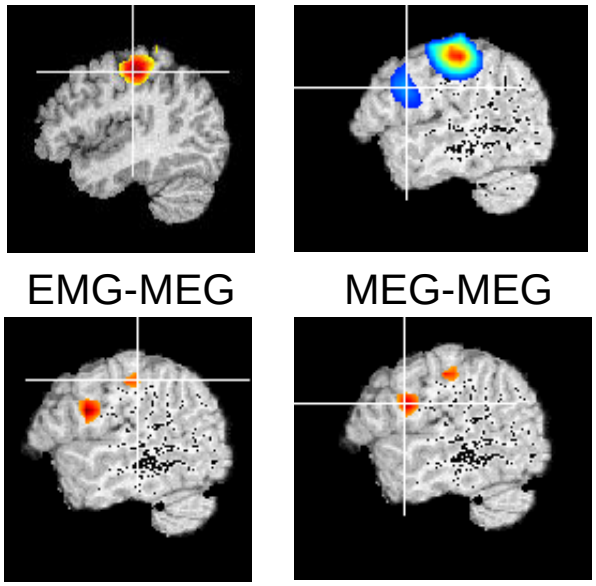
Calculation of coherence between all voxel combinations

Identification of most densely connected voxels

EMG-MEG coherence vs. CDE

- Same areas identifiable via CDE and EMG-MEG coherence in real data
  - Accuracy around MEG spatial resolution

Single subject



Kujala et al Neuroimage 2008

EMG-MEG coherence vs. CDE

- Same areas identifiable via CDE and EMG-MEG coherence in real data
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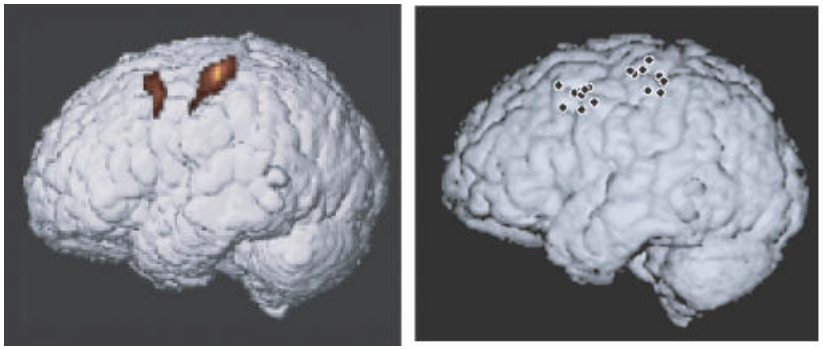
Group-level data



M1 as reference with SPM

CDE

Kujala et al Neuroimage 2008

Connectivity in a continuous reading task (RSVP)

- Rapid Serial Visual Presentation (RSVP) of words forming connected text

fast (~25 words/second)

medi (~15 words/second)

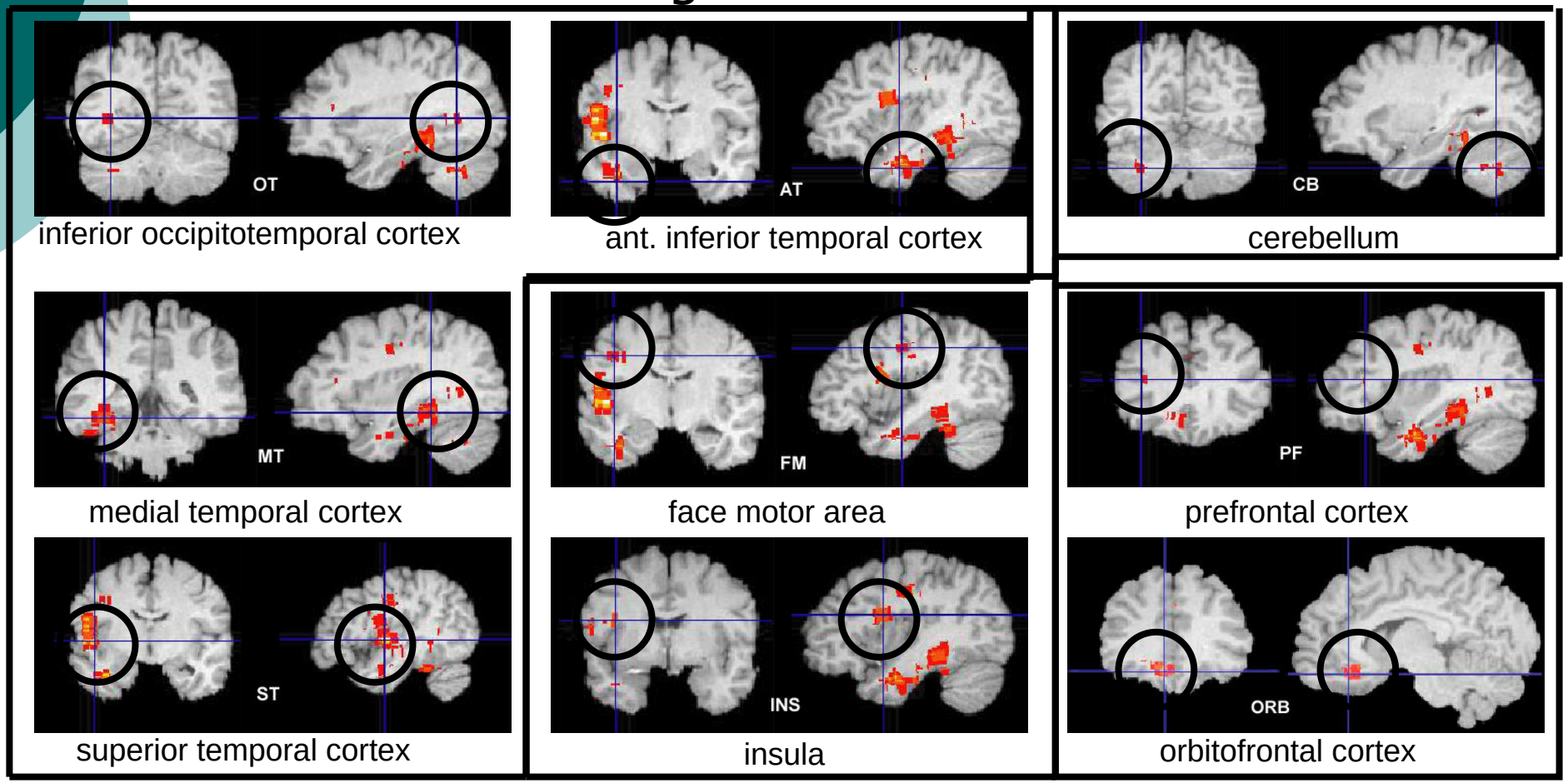
slow (~8 words/second)

isolated words (0.3 words/second)

Kujala et al Cereb Cortex 2007

RSVP: Connectivity at the group level

- Networks starting from CDE reference areas



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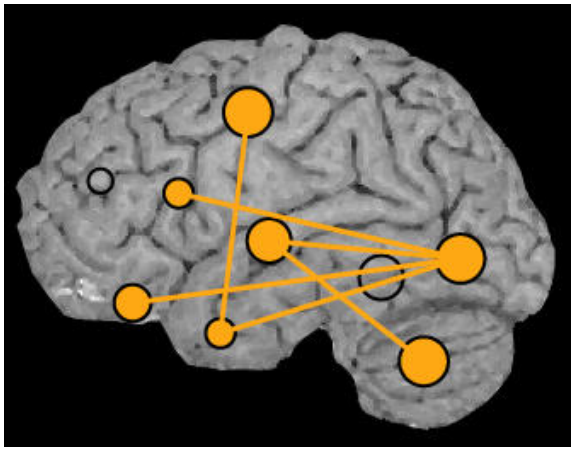
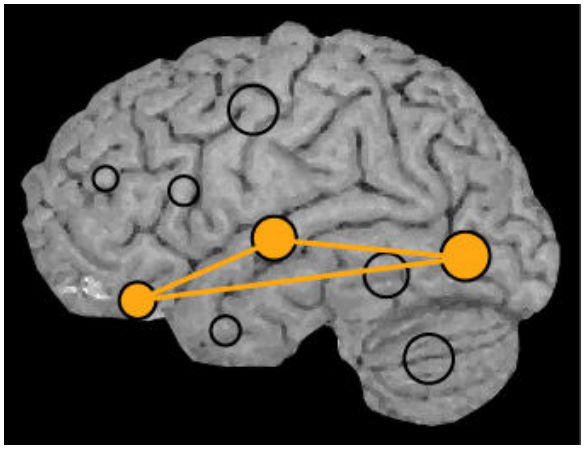
RSVP: Task effects

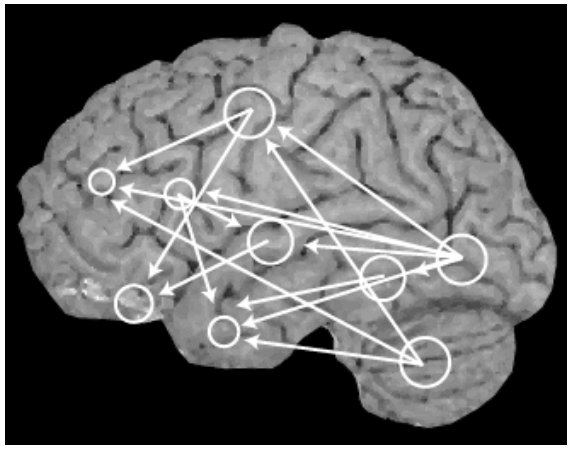
- Comparison of phase-coupling between conditions (SI)
- Estimation of directed influence using Granger causality



RSVP>word-by-word



fast/medi>slow



causality (RSVP)

Kujala et al Cereb Cortex 2007

Summary

- Coactivation/causality analysis done typically either at sensor level or for ROIs/most active areas
- Possible to image rhythmic activity and interactions, e.g., with DICS
  - Both in continuous and event-related tasks (event-related coherence under development)
- Identification of areas with coherence, i.e., coactivation with the reference area
  - Causality evaluated only for the defined network
- External reference signals beneficial, possible to start from cortico-cortical coherence

Questions

- How valid are the beamforming estimates?
  - What part of the detected coupling results from leakage between spatial filters?
- How valid is coherence as a measure in identification of areas?
  - Phase coupling and causality?
- Correspondence between brain areas identified as nodes in network analysis and areas showing task-specific activation?
- Specificity of the networks to the task and input/output modality?

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