MRC Cognition and Brain Sciences Unit

Aalto University School of Science

MEG: Physics and forward modelling

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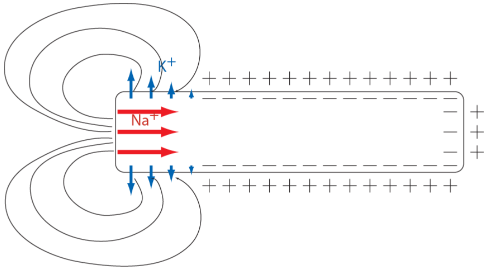
EMA seminar series 2013

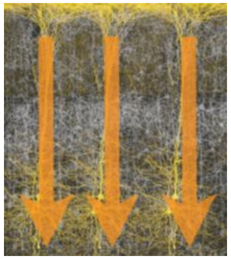
Contents

1. Physics

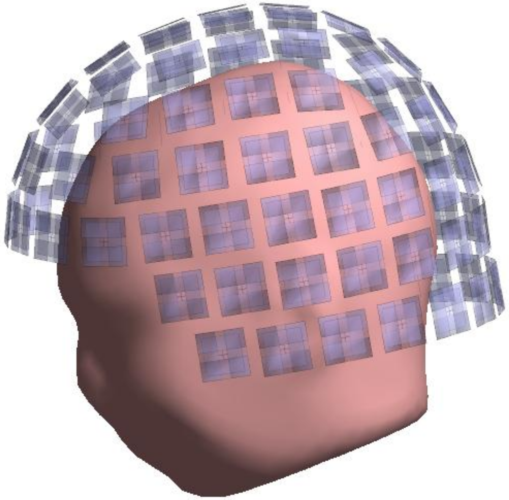
$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'} \frac{[\vec{J}(\vec{r}\,') + \vec{J}_v(\vec{r}\,')] \times (\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3} dV'$$

2. Source model

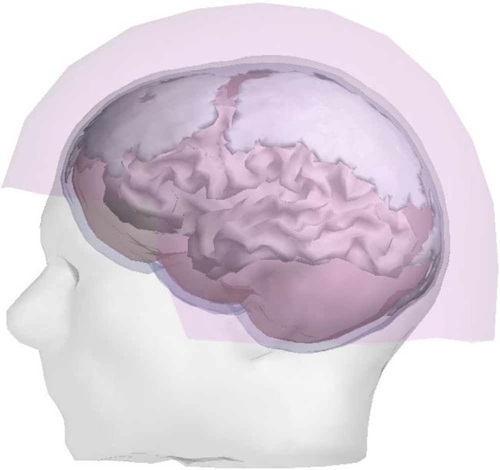




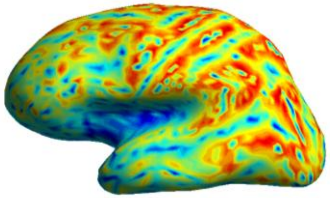
3. Sensor model

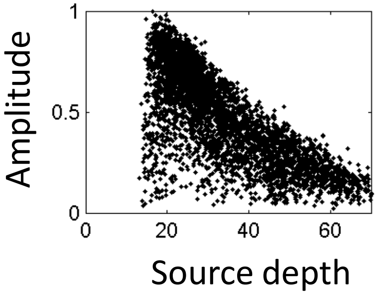


4. Conductivity model



5. MEG vs. EEG

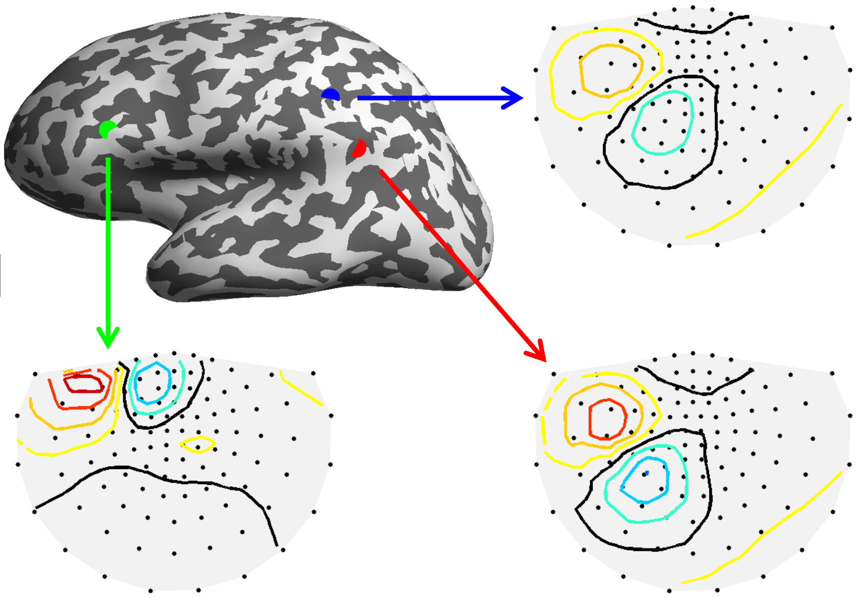




Intro Forward modelling?

What?

- Generally: compute physical field generated by known sources
- Here: compute MEG/EEG signal generated by neural activity.

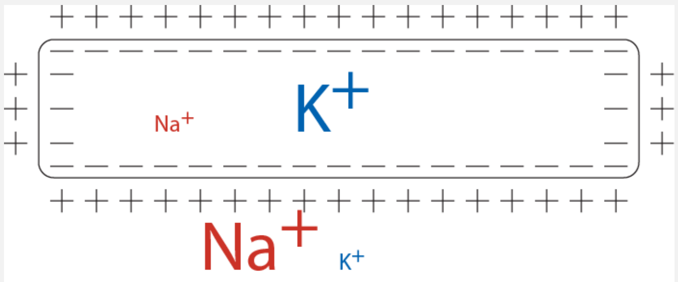


Why?

- To understand the origins of signal
- To design/optimize sensor setups
- To be used in source estimation.

1 Physics simplified

Excitable cell, resting:

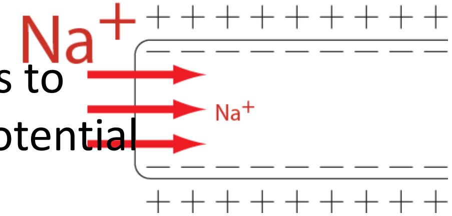


- Concentration gradient
- Ion channels: Na closed, K open
  - Polarised membrane/ membrane potential
- No currents or fields.

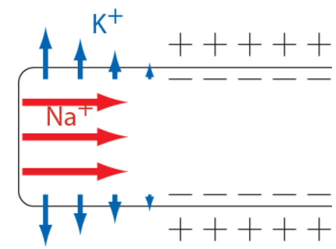
All currents generate magnetic field:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'} \frac{\vec{J}(\vec{r}\,') \times (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3} dV'$$

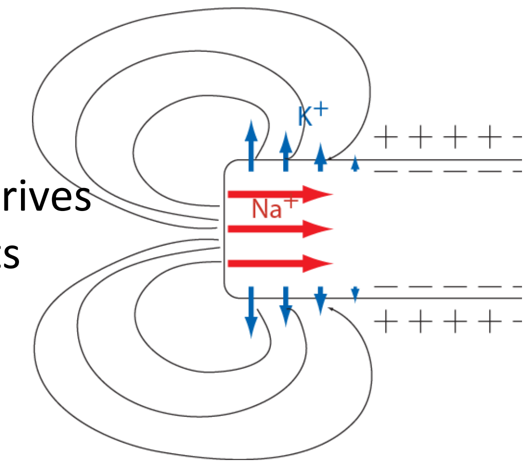
Na flows in & starts to raise membrane potential



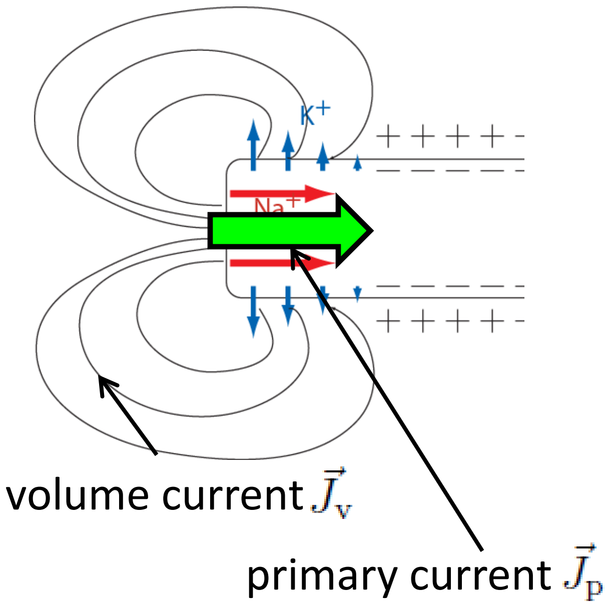
Na spreads,
K flows out to restore membrane potential



Electric field drives return currents



1 & 2 Source model and equations



Macroscopic source model

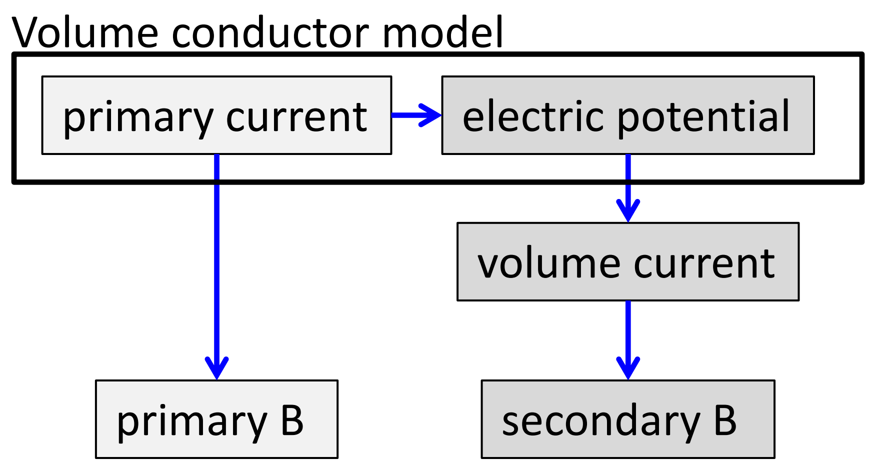
- Assume tissue continuum
  - No intra- and extracellular space
  - No cellular membrane, membrane currents
  - No intra/extra-cellular currents
- Source activity: primary current
- Total current $\vec{J}$:
  primary current $\vec{J}_\mathrm{p}$ + volume current $\vec{J}_\mathrm{v}$

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'} \frac{\vec{J}(\vec{r}\,')\times(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3}dV'$$

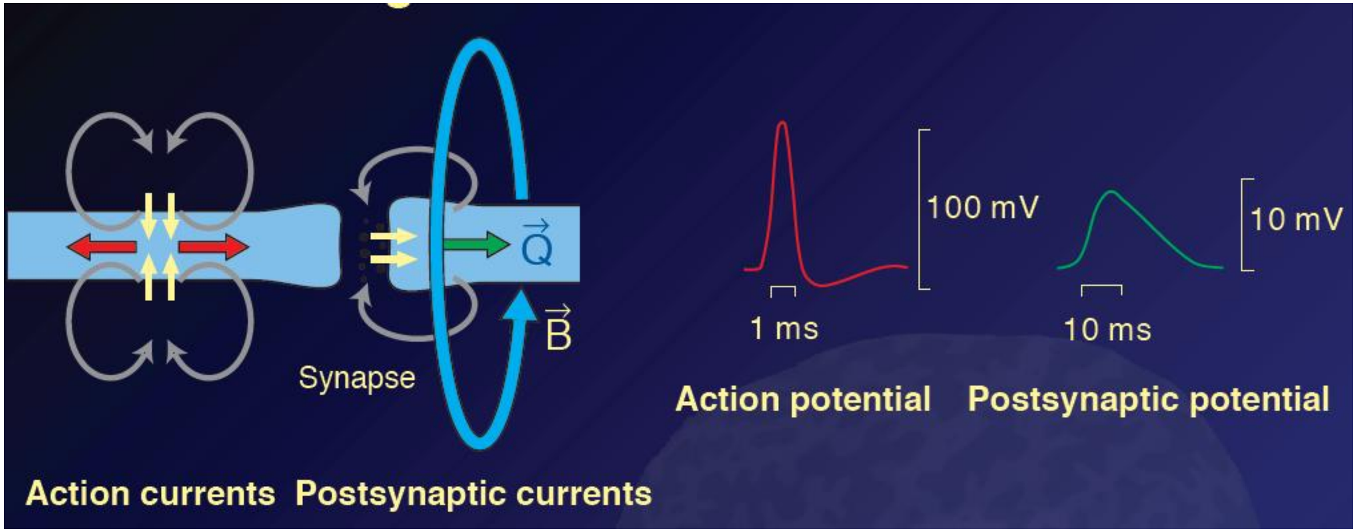
$$\vec{J} = \vec{J}_\mathrm{p} + \vec{J}_\mathrm{v}$$

$$\vec{J}_\mathrm{v} = -\sigma\nabla\phi, \quad \nabla\cdot(\sigma\nabla\phi) = \nabla\cdot\vec{J}_\mathrm{p}$$

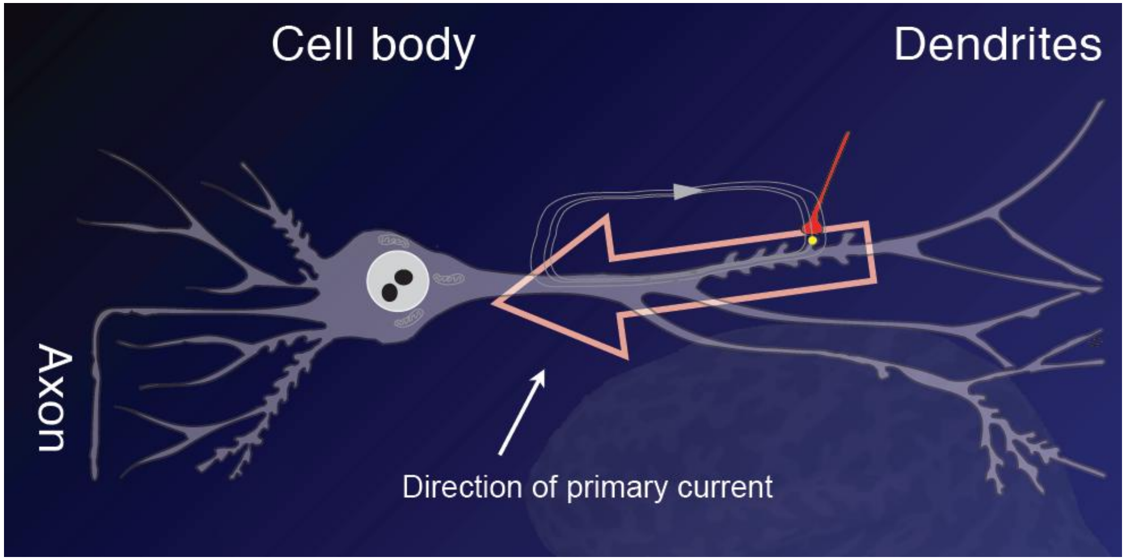
ϕ electric potential
σ conductivity



Neural sources

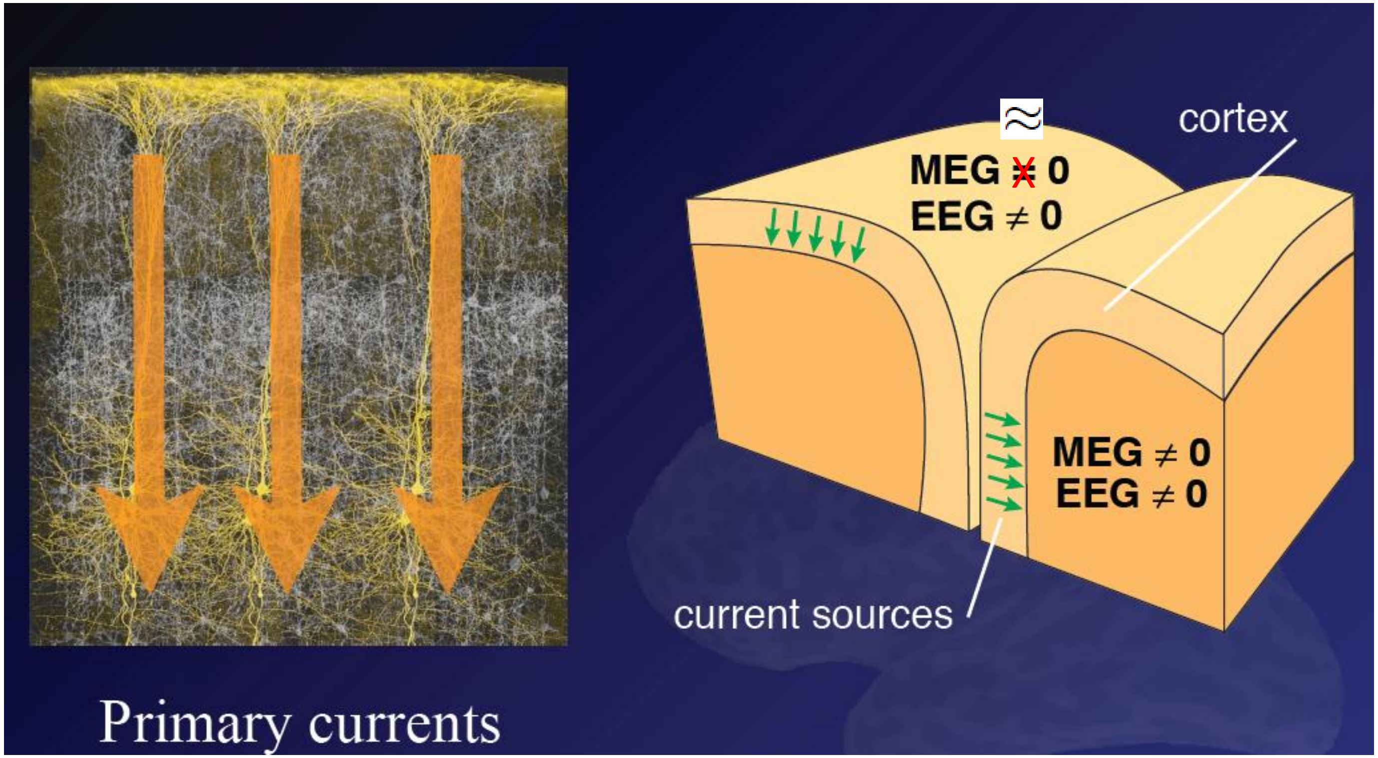


- Postsynaptic currents:
  dipole, attenuates ~ $1/r^2$
- Action currents:
  de- ja repolarisation close to each other → quadrupolar field, attenuates ~ $1/r^3$
- Action currents can be measured only in tissue.



Pics: Matti Hämäläinen

Cortical sources



Pic: Matti Hämäläinen

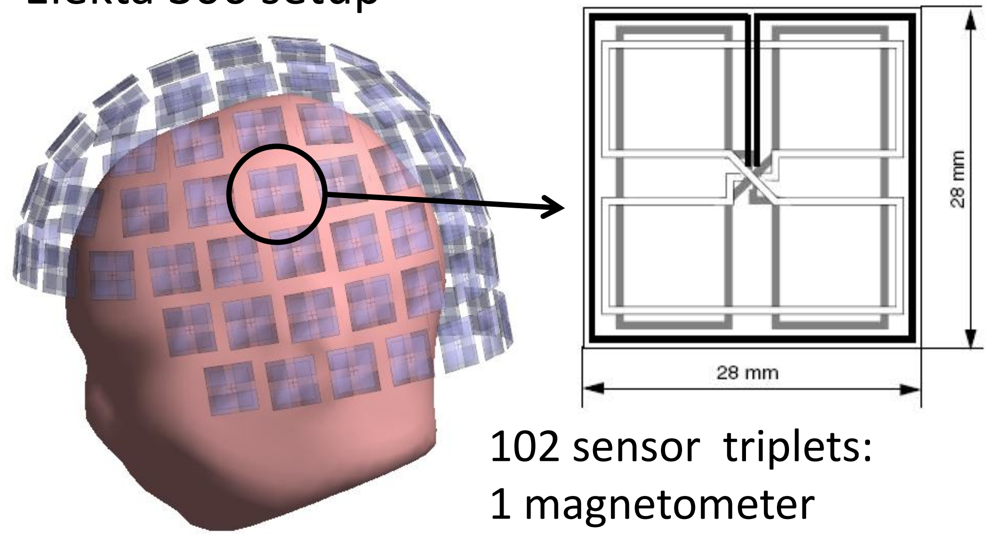
- EEG and MEG have approximately the same neural source: primary current density in cortex
- Cellular source: postsynaptic currents in pyramidal neurons
- Sources are (anatomically) oriented normal to cortical surface
- A small patch of cortex, ~1cm^2, thousands of activated neurons: dipole
- Distributed source: primary current discretized into dipoles (N typically 5000-10000)

Sensor model

Sensor types

- Magnetometer: B_z
- Planar gradiometer: $\Delta B_z/\Delta x$, $\Delta B_z/\Delta y$
- Axial gradiometer: $\Delta B_z/\Delta z$
- Sensor size ~ 2 cm.

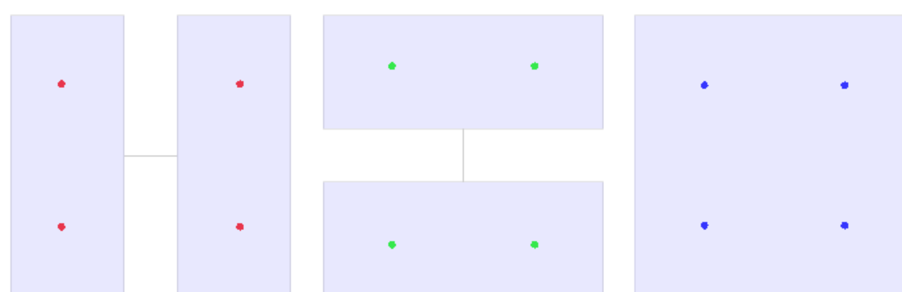
Elekta 306 setup



102 sensor triplets:
1 magnetometer
2 planar gradiometers

Sensor model: numerical integral

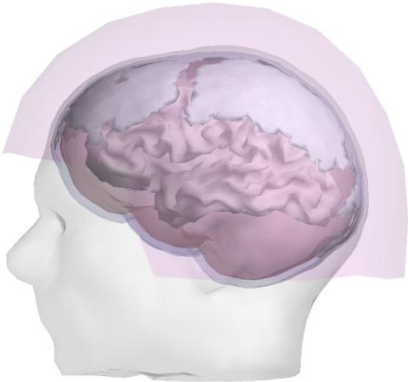
- Each sensor: set of points (1 to 8).
- For each point, compute B_z
- Weighted sum over points.



GM1 GM2 MM

4 Volume conductor model

- MEG is generated by both primary currents and volume currents



$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'} \frac{[\vec{J}_\mathrm{p}(\vec{r}\,') - \sigma(\vec{r}\,')\nabla\phi V(\vec{r}\,')] \times (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3} dV'$$

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \vec{J}_\mathrm{p}$$

- EEG is generated by primary currents and ”communicated” via volume currents
- To solve the volume currents, conductivity distribution in the head needs to be modelled: volume conductor model.

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Misunderstandings or strange statements:

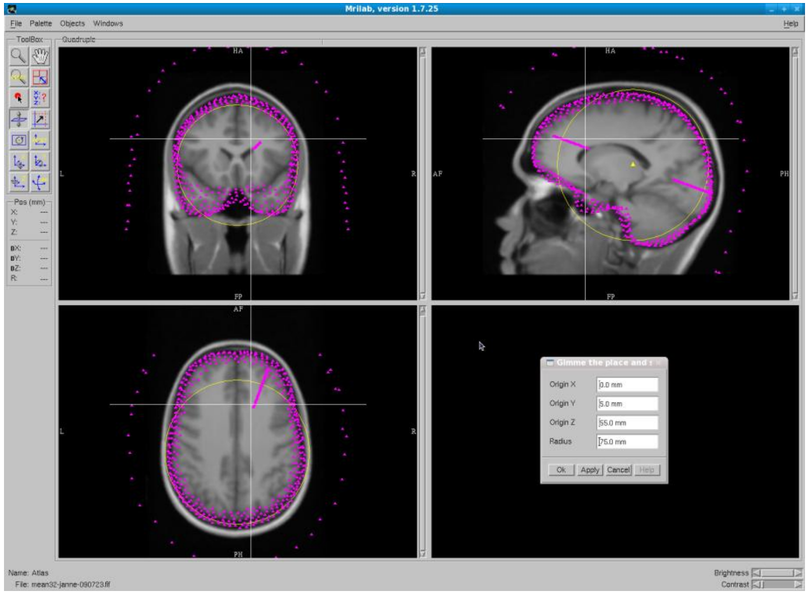
”The conductivity profile of head does not distort MEG signals”

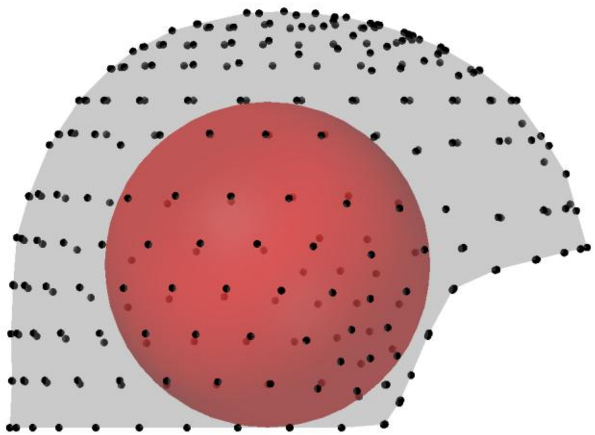
”Volume currents have no effect on MEG”

”The conductivity profile of head has more effect on EEG than on MEG”.

4 MEG volume conductor models

- Spherical models
  - Local spheres model
  - Perturbed sphere
- 1-shell realistic model
- 3-shell realistic model



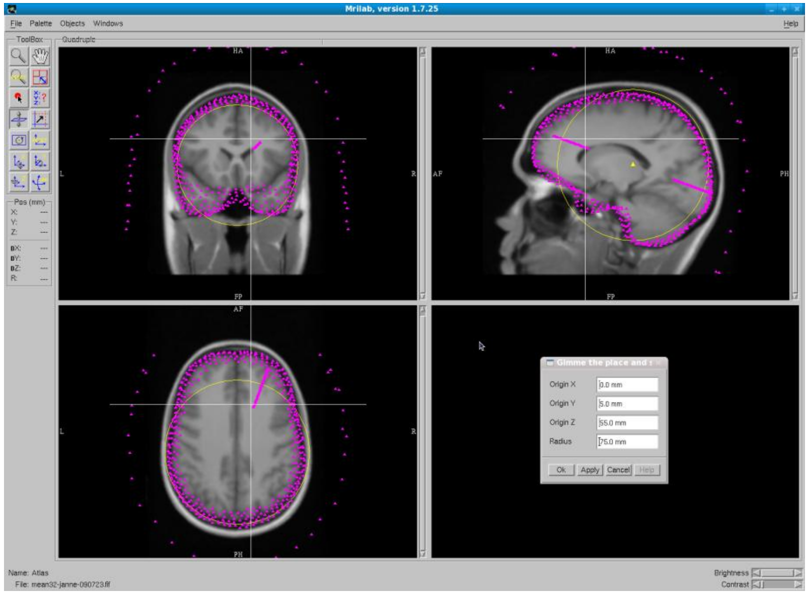


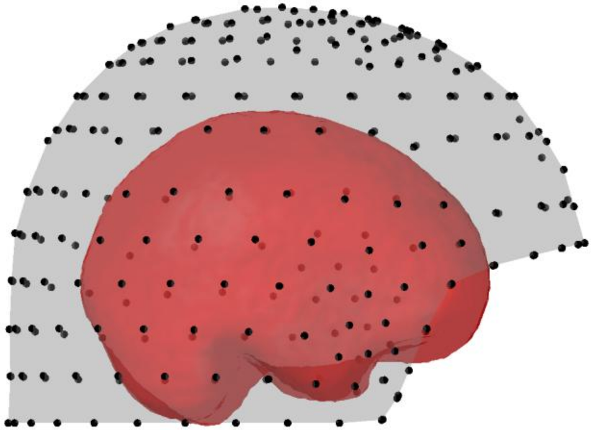
Spherical model

- Radial sources produce no field
- Radial conductivity profile has no effect on field
- Radial field of a tangential source same as in vacuum
- One free parameter: origin
- Fitted globally or locally to inner skull

4 MEG volume conductor models

- Spherical models
  - Local spheres model
  - Perturbed sphere
- 1-shell realistic model
- 3-shell realistic model



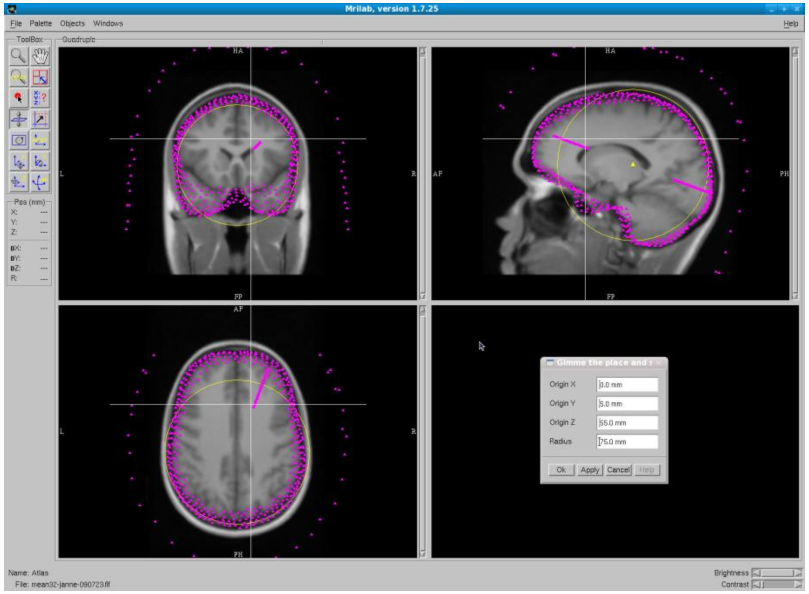


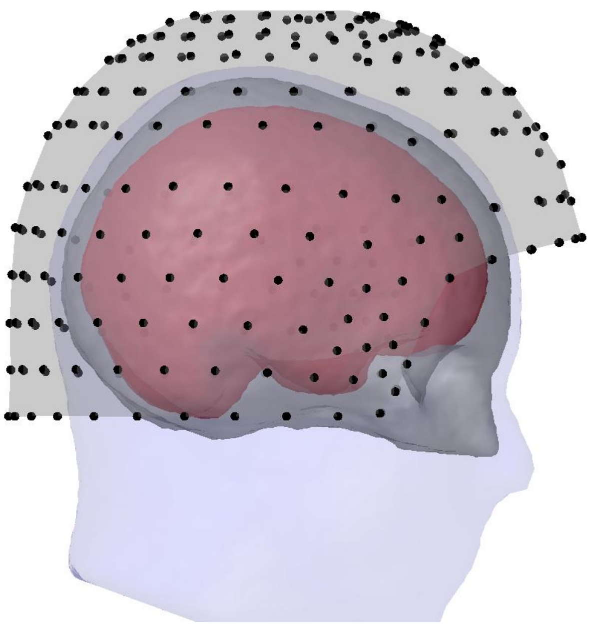
1-shell model

- Most of the currents inside the skull
- Omit currents in skull and scalp
- Reasoning: head almost spherical, skull almost insulator

4 MEG volume conductor models

- Spherical models
  - Local spheres model
  - Perturbed sphere
- 1-shell realistic model
- 3-shell realistic model

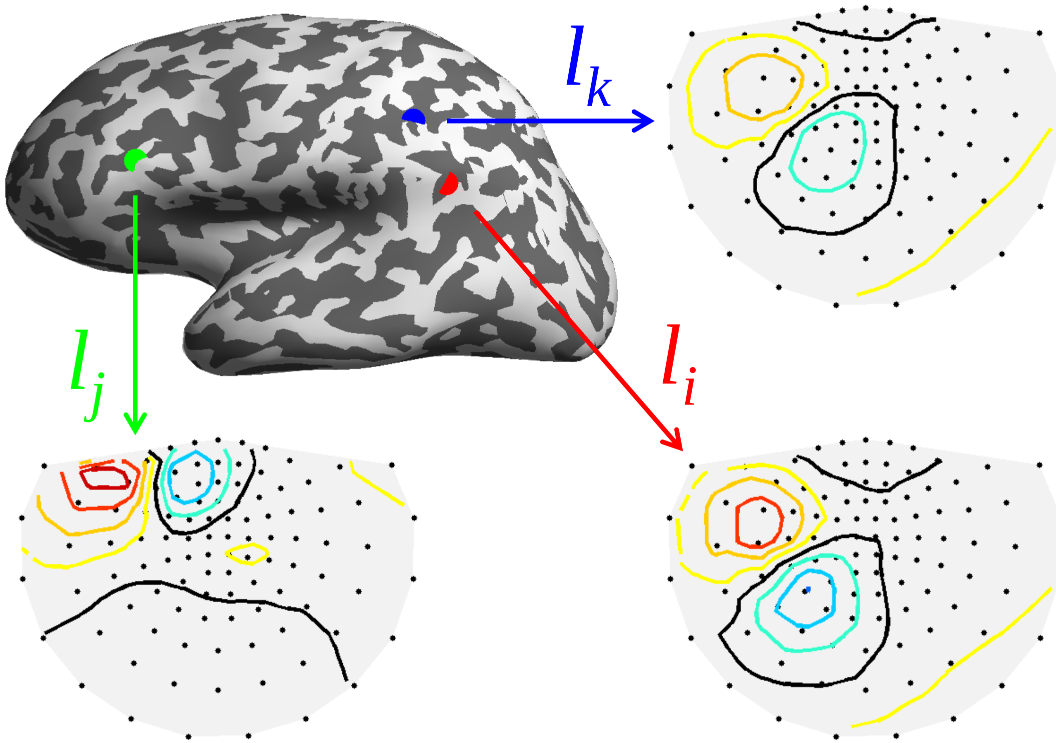




3-shell model

- Most accurate easy-to-generate model
- Inner skull, outer skull, scalp
- Sources of error:
  - Poor MRI contrast for skull
  - CSF, fiber anisotrophy, air cavities omitted
  - Inaccurate numerical solution due to crude meshing or poor solver

The result: lead fields



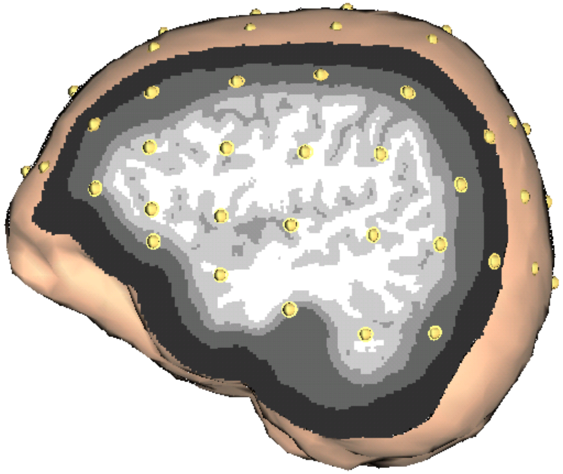
Lead vector $\boldsymbol{l}_i$:
signal produced in all sensors by a unit-strength oriented source in $\boldsymbol{r}_i$

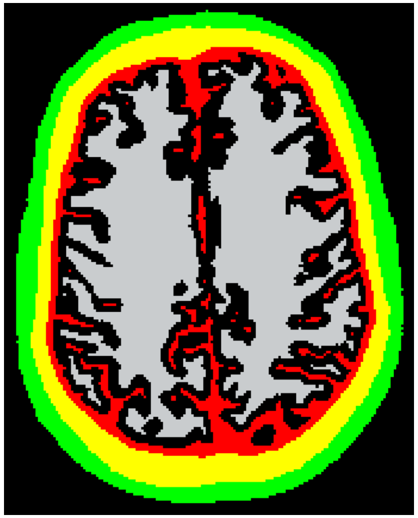
- Lead-field matrix: $\boldsymbol{L} = [\boldsymbol{l}_i \ \dots \ \boldsymbol{l}_N]$
- Linear measurement model: $\boldsymbol{m} = \boldsymbol{L}\boldsymbol{s} + \boldsymbol{n}$

4 EEG volume conductor modeling

3-shell model

- Brain, skull, scalp
- Spherical model or realistic geometry?
  - Sphere... Poor accuracy
  - Standard head... wouldn't bet my money on this
  - Morphed?
- Personal model based on MR / CT sets
  - Numerical computations: BEM, FEM, FDM: all OK, when done properly
  - In 3-shell model, BEM is a natural choice
- In the future?
  - 4-shell model (incl. CSF)
  - Skull fine-structure: spongious / compact
  - White-matter anisotrophy

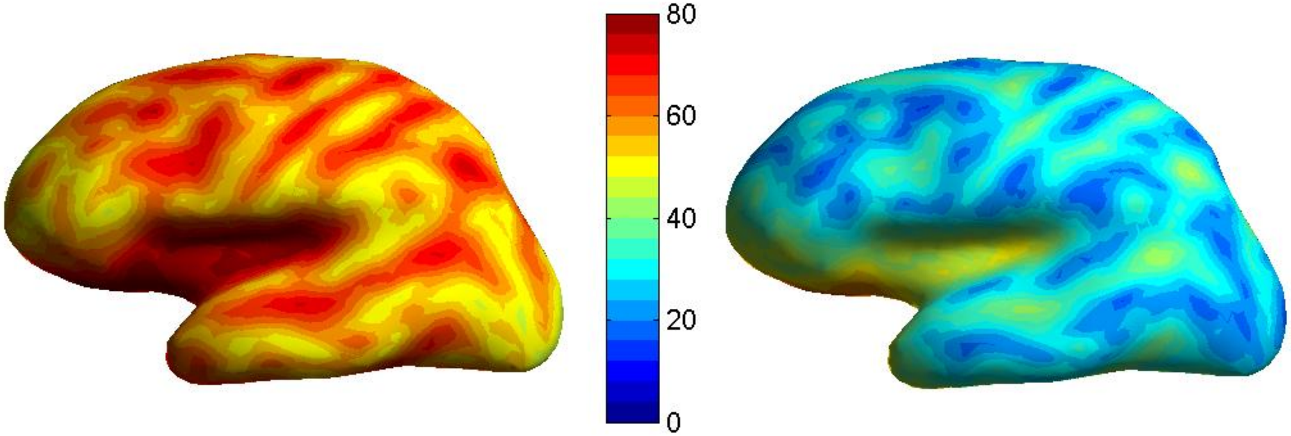


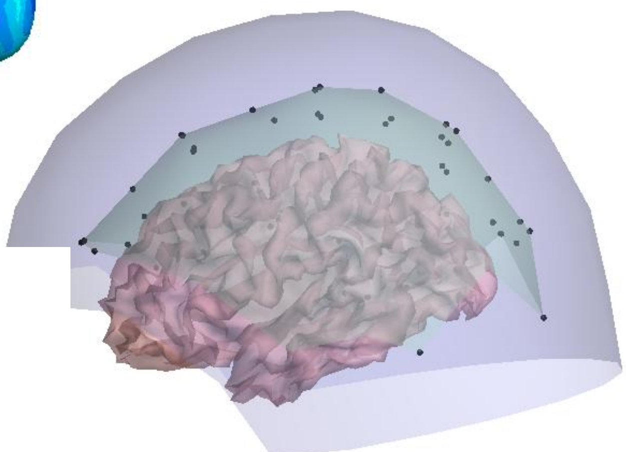


Pics: C. Wolters

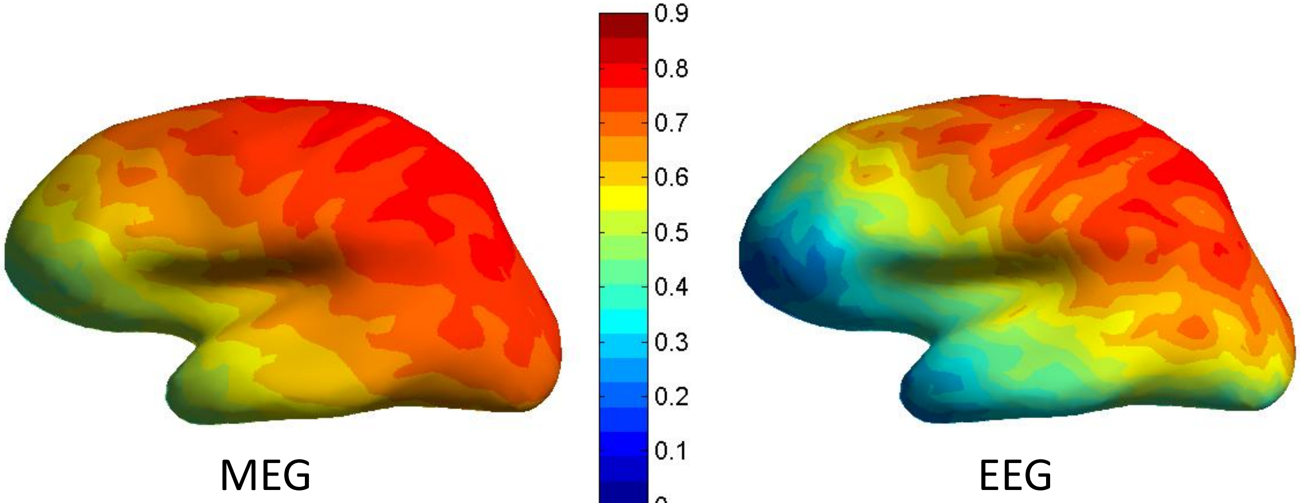
5 EEG vs. MEG: Geometry

- Source—sensor distance: smaller in EEG





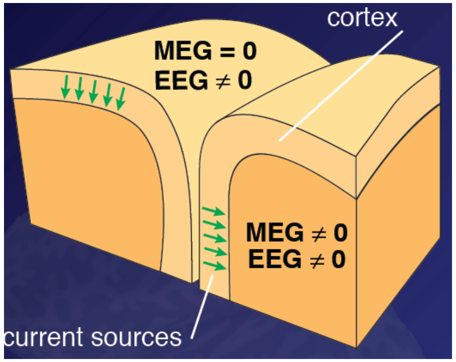
- Coverage: typically better in MEG

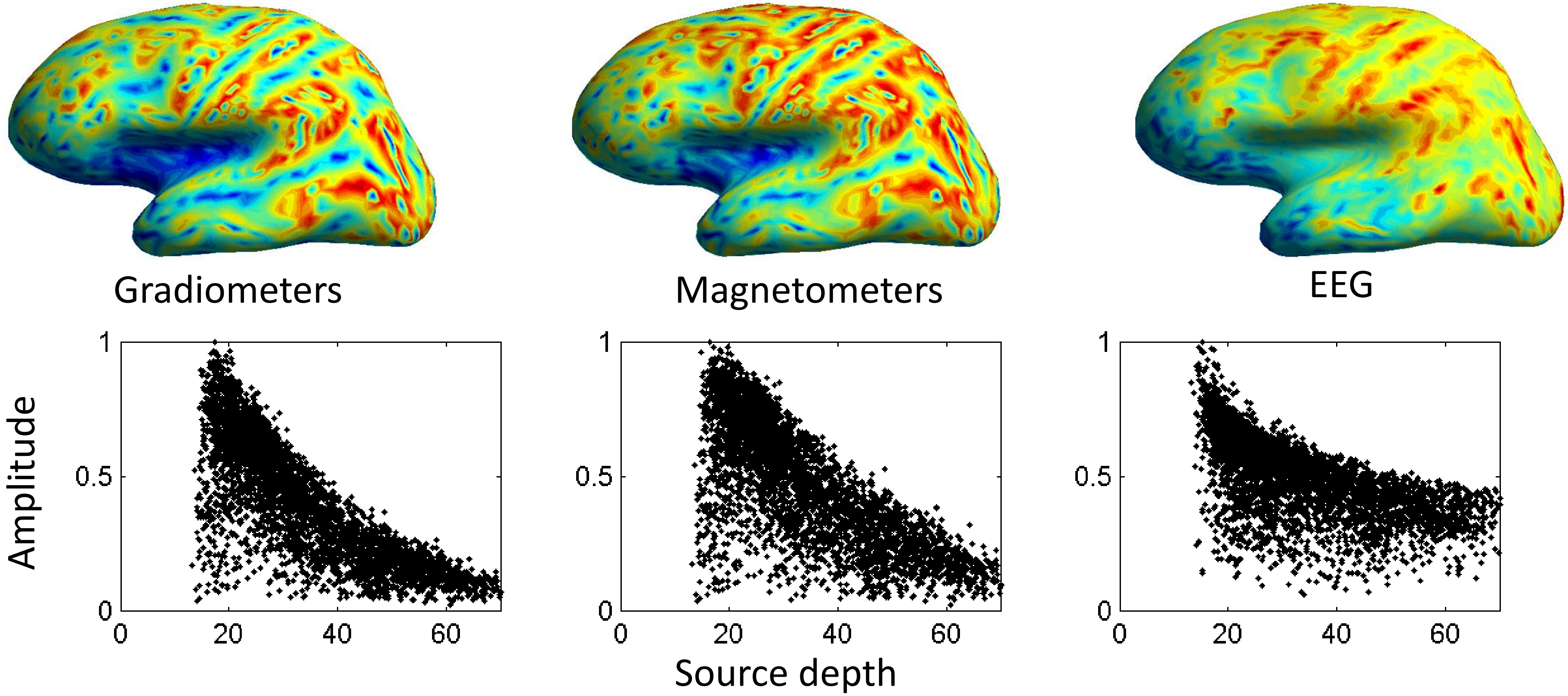


5 Source strength / signal amplitude

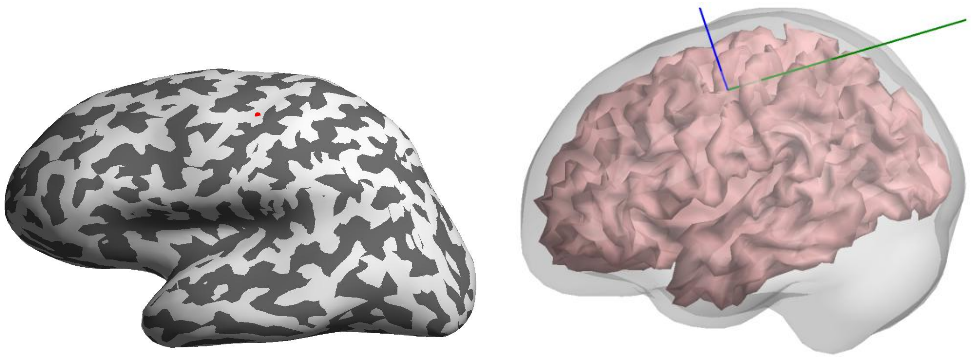
Signal amplitude for normally oriented sources:

- As depth increases,
  EEG > Magnetometers > Gradiometers
- Radial sources: small MEG signal
  - Bottom of sulci, top of gyri!

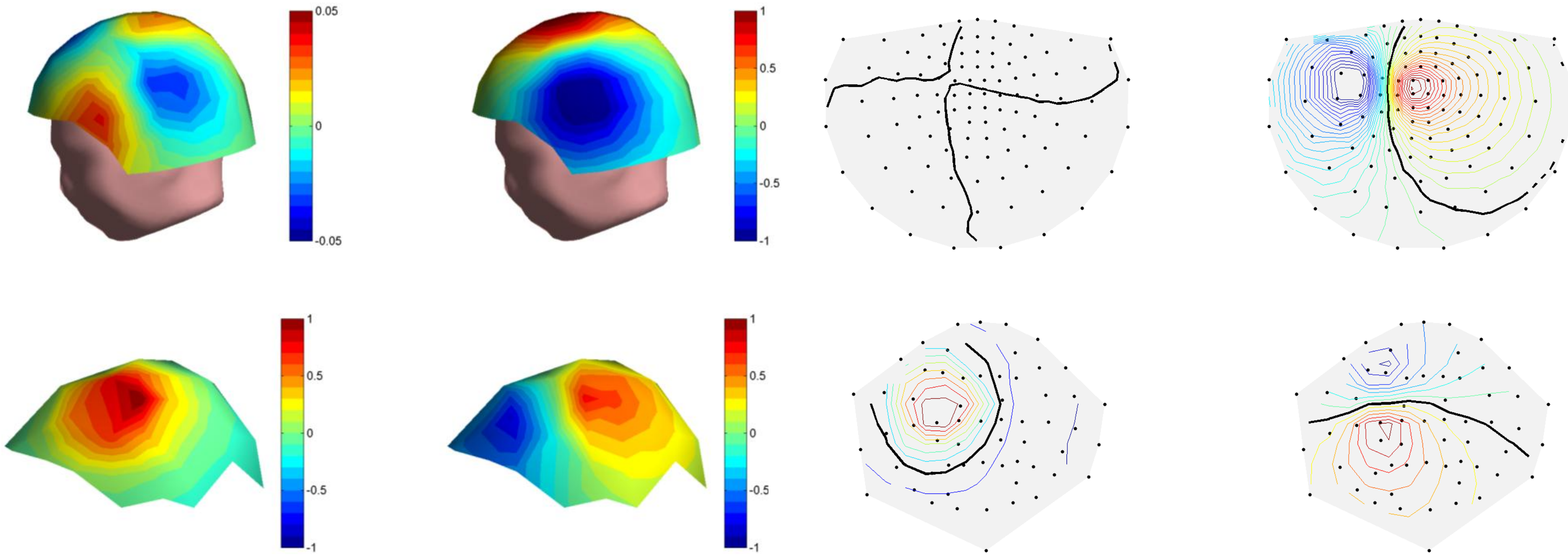




Radial and tangential sources



Dependency of signal amplitude on source orientation:
large in MEG, in general small in EEG

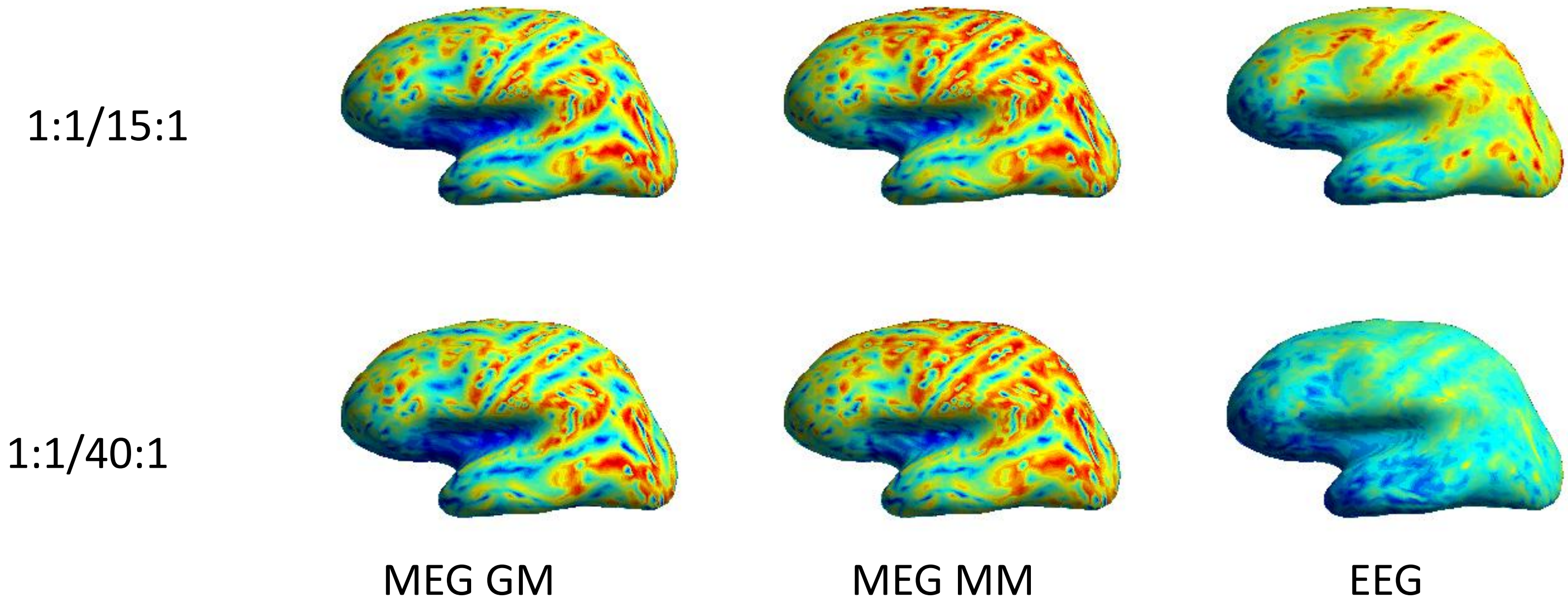


Radial

Tangential

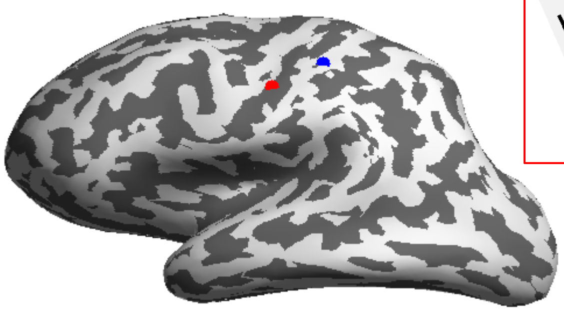
5 Skull conductivity

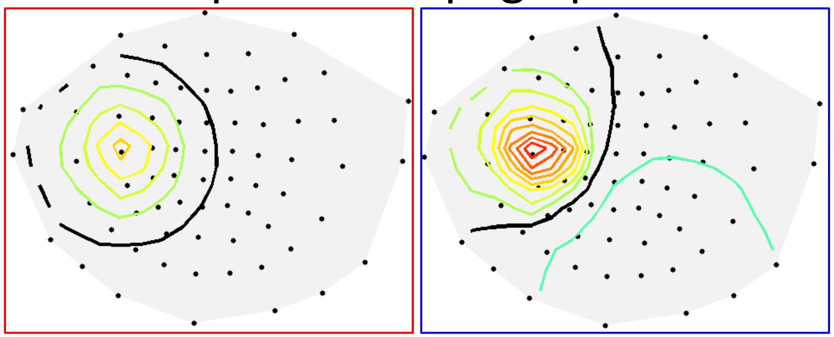
- EEG depends on skull conductivity
  - Amplitude depends strongly, topography less so.
- MEG doesn’t that much
  - But assuming skull insulator would add errors.

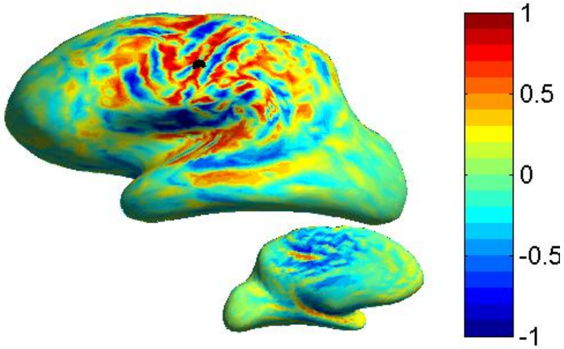


5 Correlations between topographies

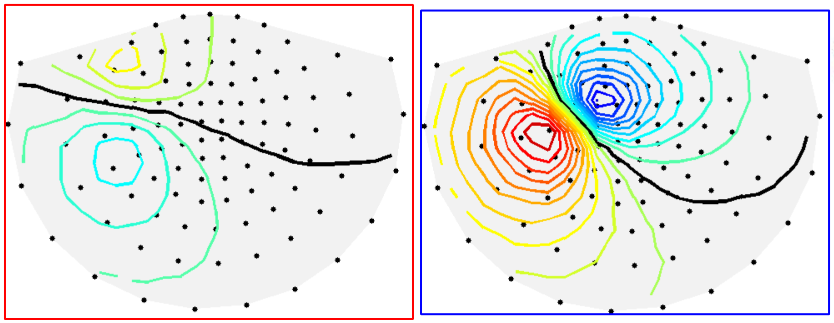
- Topographies of different sources are often correlated
- These correlations are different for EEG and MEG
  - MEG and EEG complement each other
- Overall, MEG has less overlap across topographies.

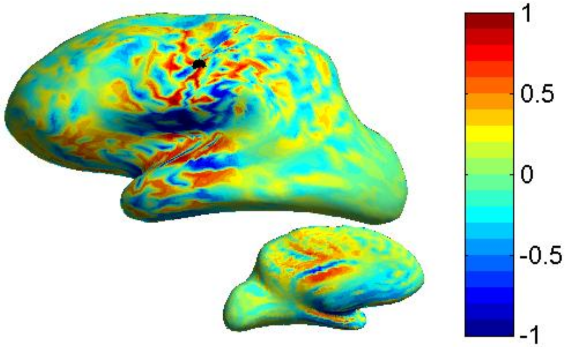






EEG: CC = 0.91





MM: CC = -0.68

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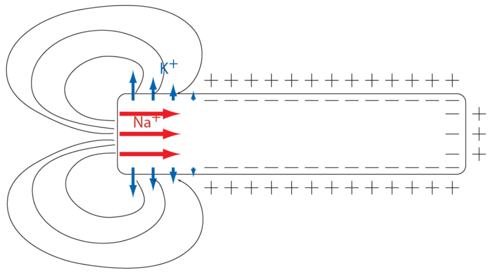

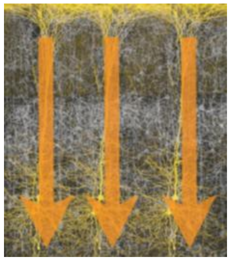

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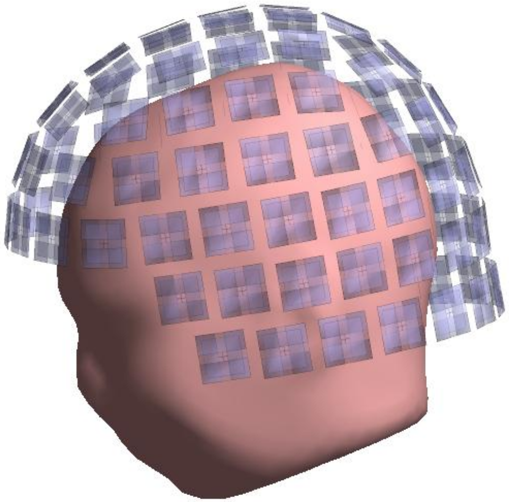

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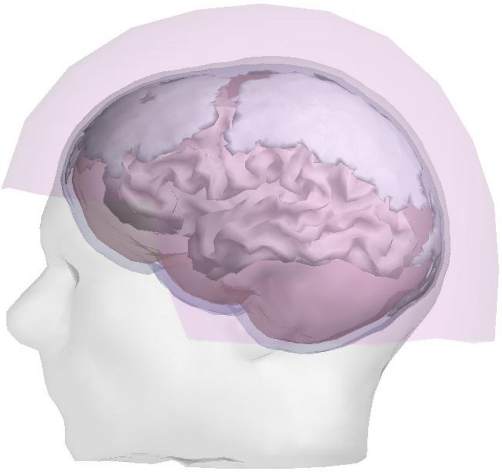

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