EEG/MEG 2:

Head and Forward Modelling

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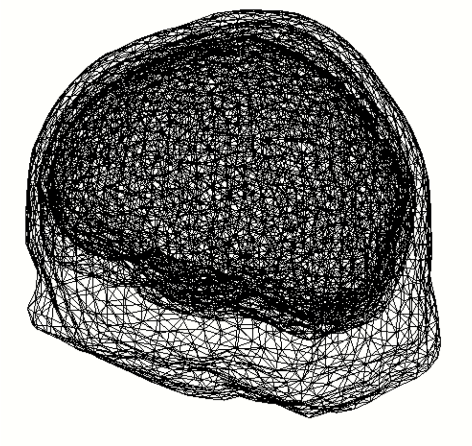
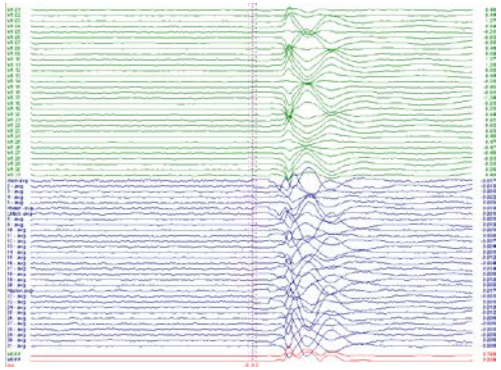
Ingredients for Source Estimation

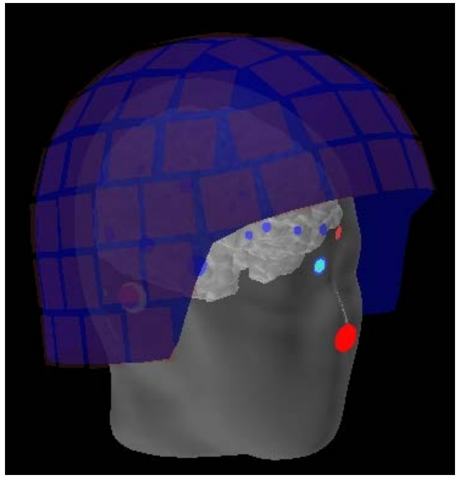
Volume Conductor/
Head Model



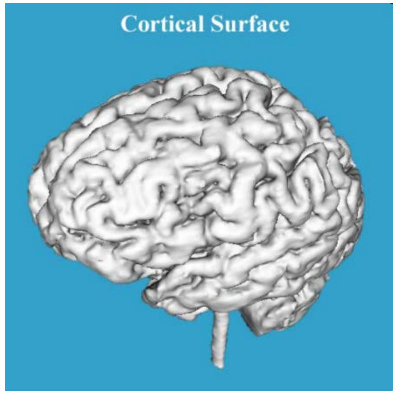
MEG data



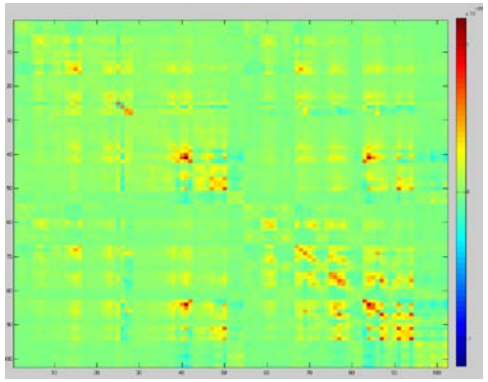
Coordinate
Transformation



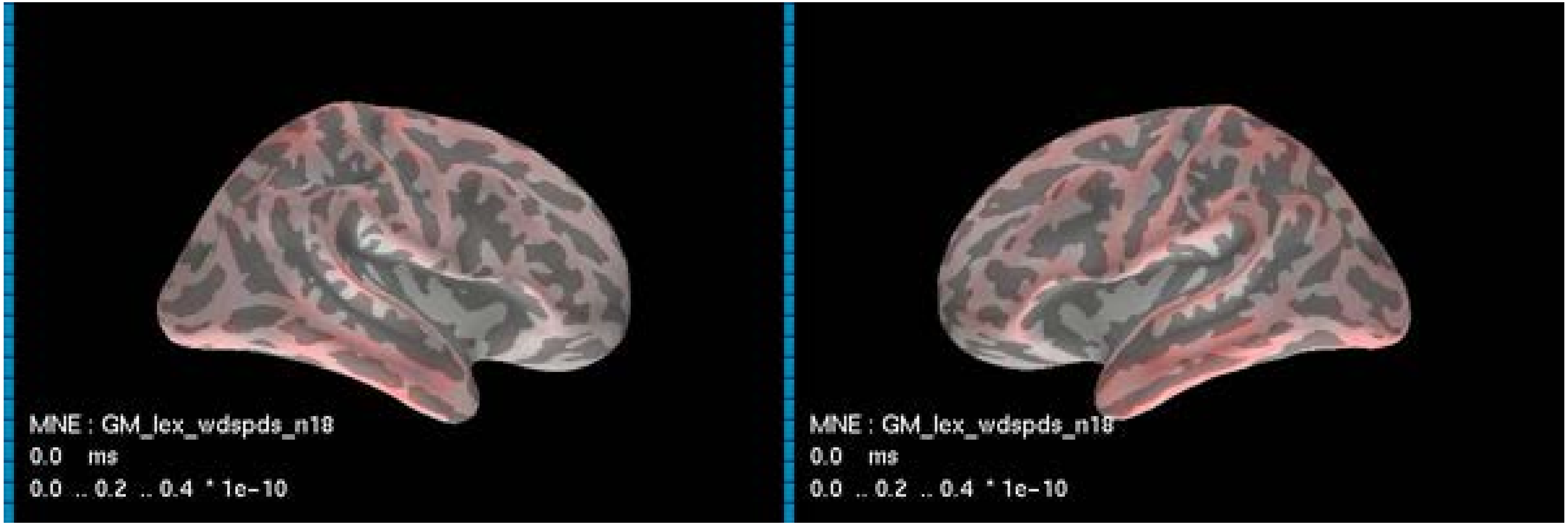
Source Space



Noise/Covariance Matrix

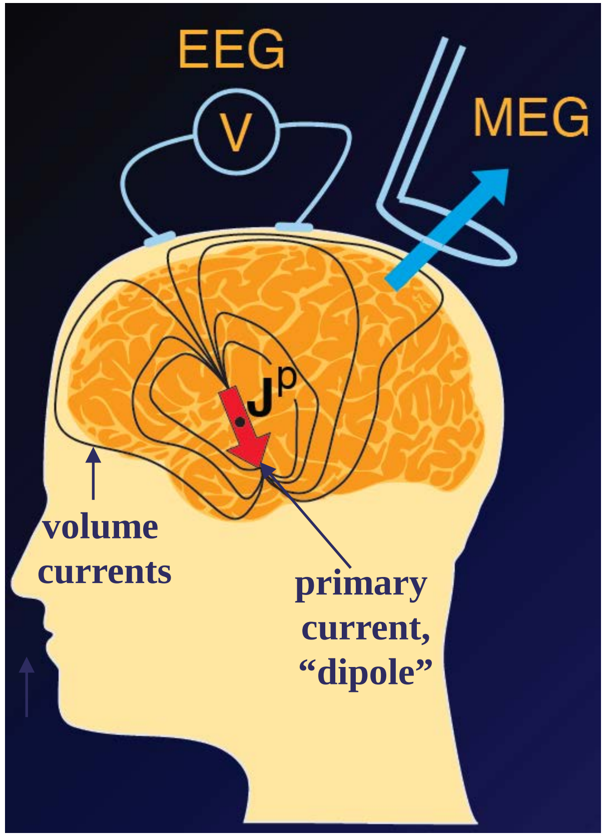


Our Goal: Spatio-Temporal Brain Dynamics
“Brain Movies”



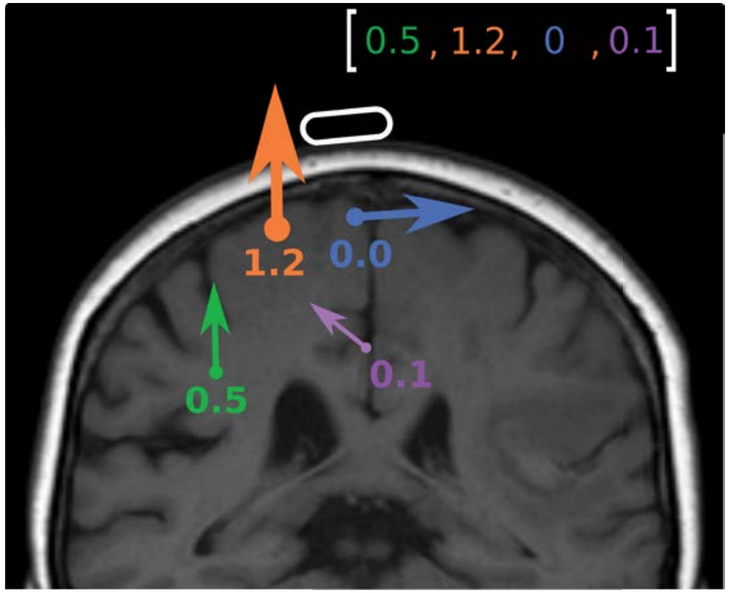
We Have To First State The Forward Problem In Order To Solve The Inverse Problem

EEG/MEG measure the primary sources indirectly



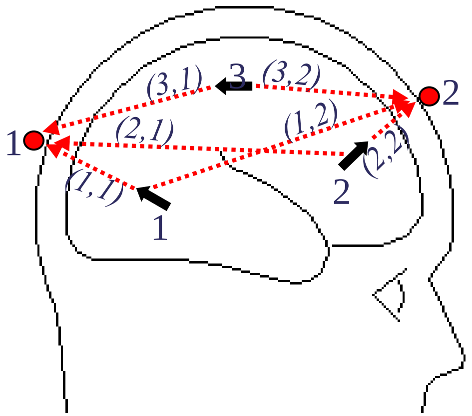
Sensors are differently sensitive to different sources

“Leadfield”



Hauk, Strenroos, Treder. In: Supek S, Aine C (edts), “Magnetoencephalography: From Signals to Dynamic Cortical Networks, 2nd Ed.”

The EEG/MEG Forward Problem



data "leadfield" dipoles

$$\begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = \begin{pmatrix} 0.5 & 0 & 0.3 \\ 0 & 1 & -0.3 \end{pmatrix} \begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix}$$

?

inversion

dipoles inverse data

$$\begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix} = \begin{pmatrix} 1.5034 & 0.1241 \\ 0.2483 & 0.9379 \\ 0.8276 & -0.2069 \end{pmatrix} * \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$$

$j_1 + j_2 = 1$

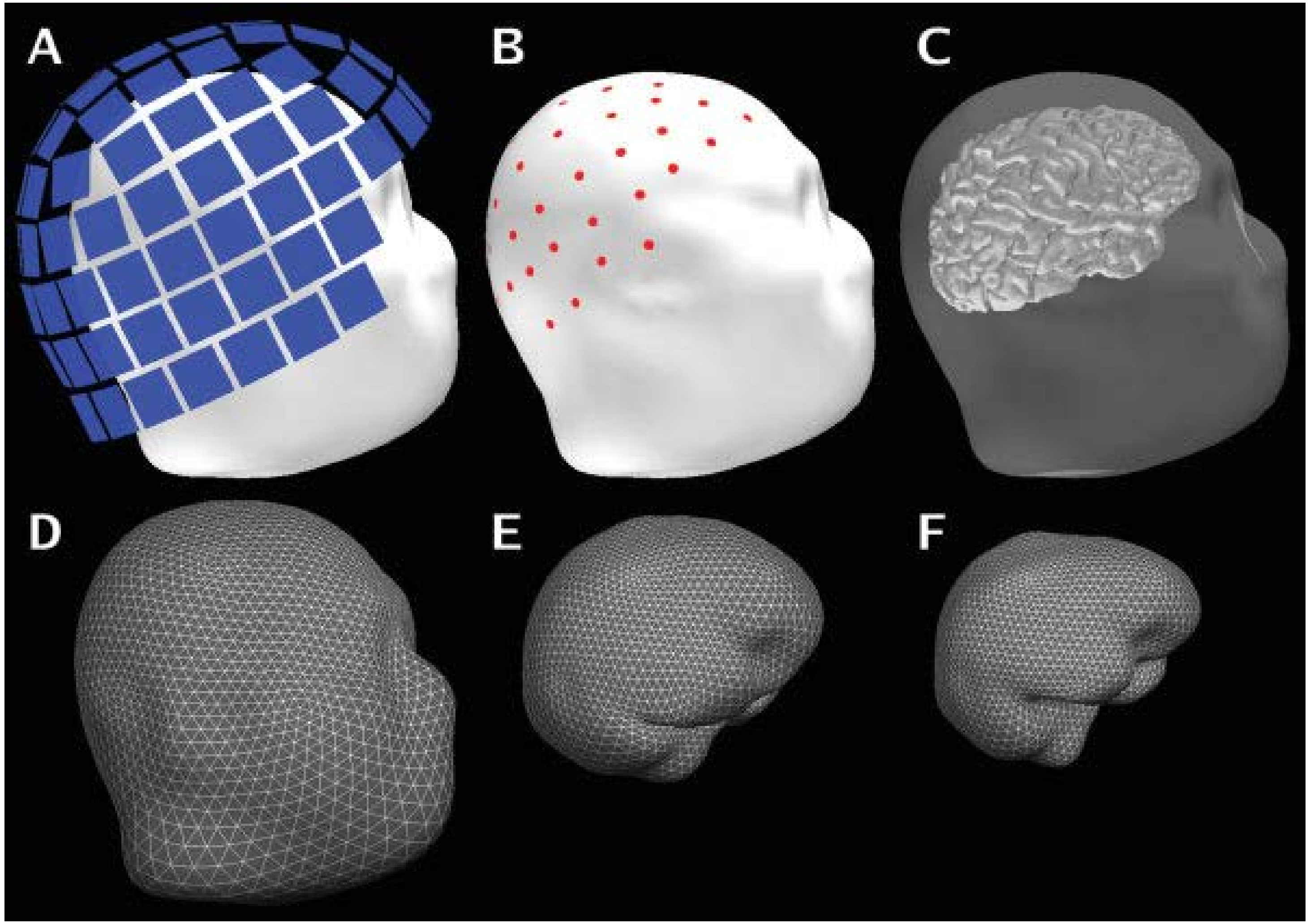
under-determined problem, no unique solution

d=Lj

d: data (n_sensors x 1) **L**: "leadfield" (n_sensors x n_dipoles), **j**: dipoles (n_dipoles x 1)

Usually n_dipoles >> n_sensors.

Ingredients for a head model

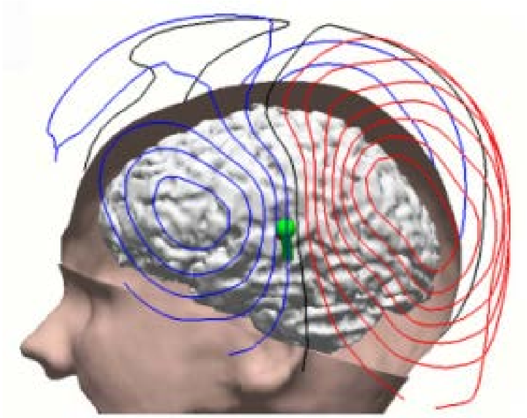


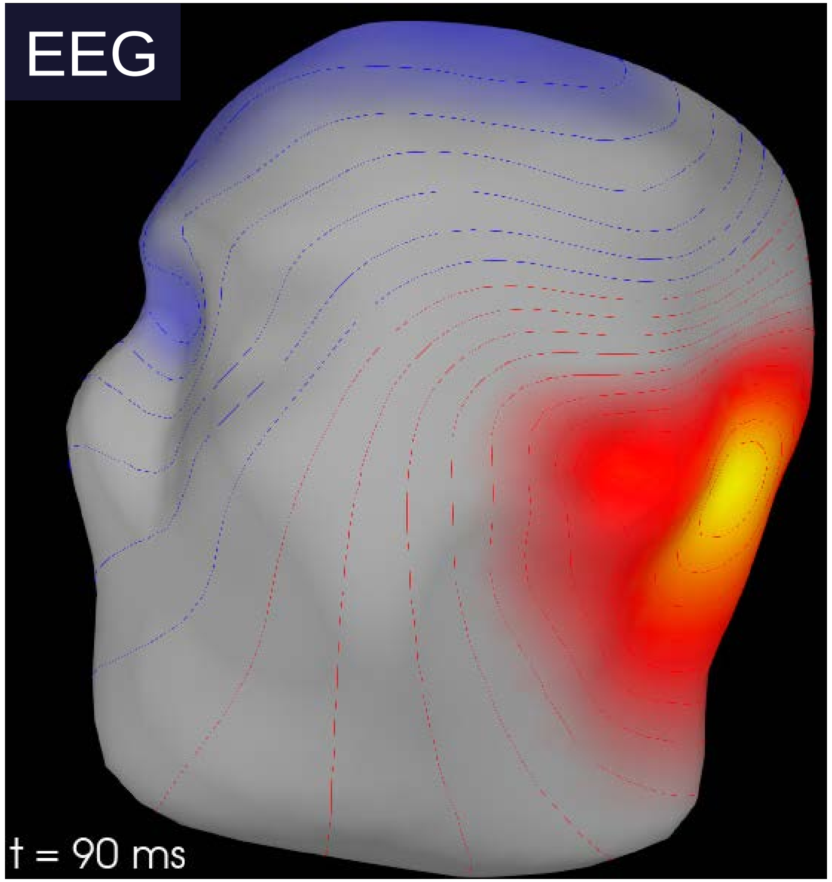
Goldenholz et al., HBM 2009
https://pubmed.ncbi.nlm.nih.gov/18465745/

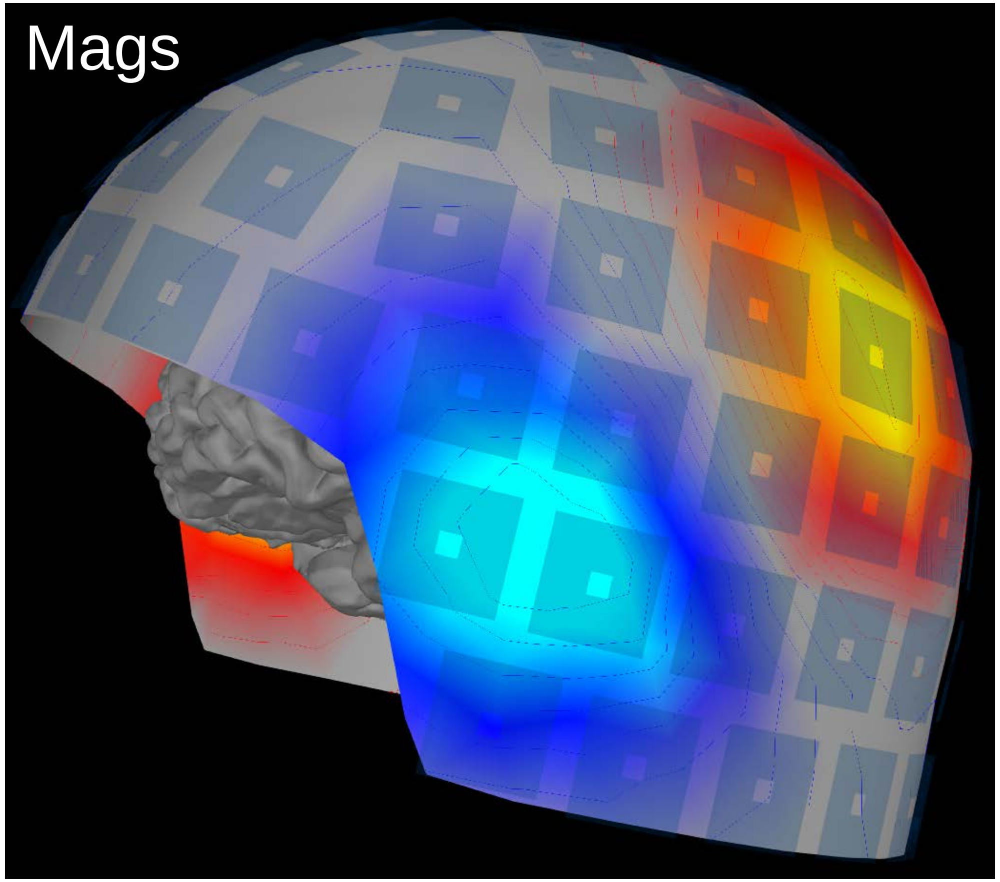
If you don’t have individual MRIs: Standard head models and spherical approximations are available.

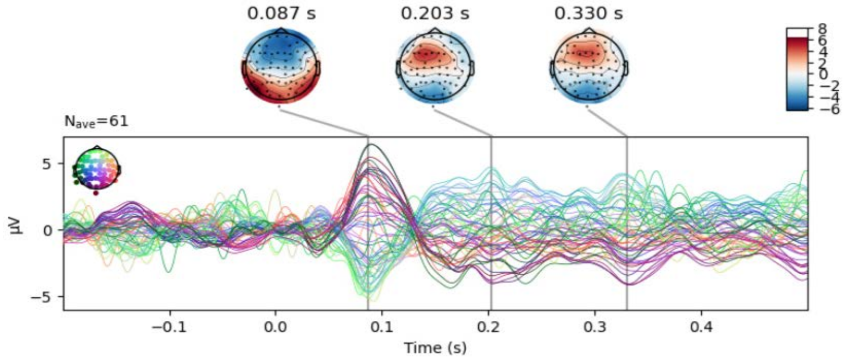
Example: Auditorily Evoked Activity

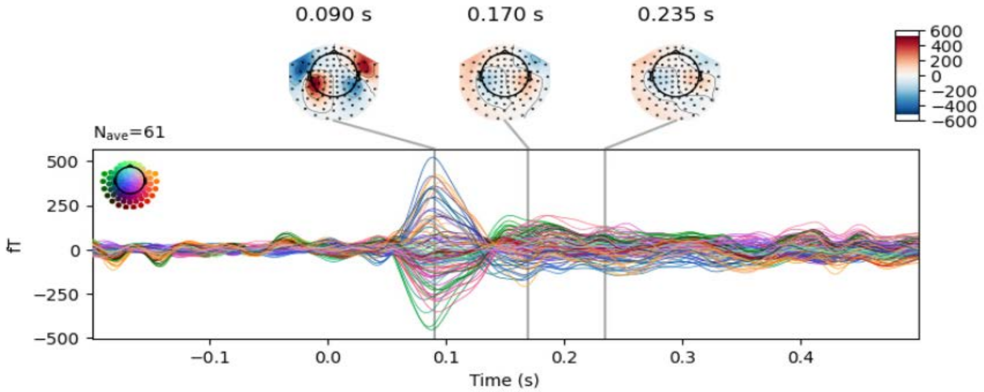
Tone to right ear





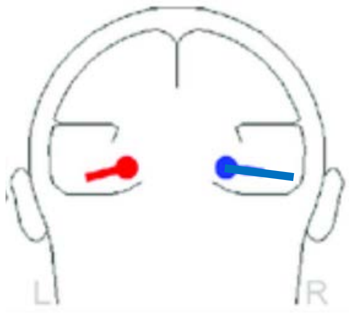


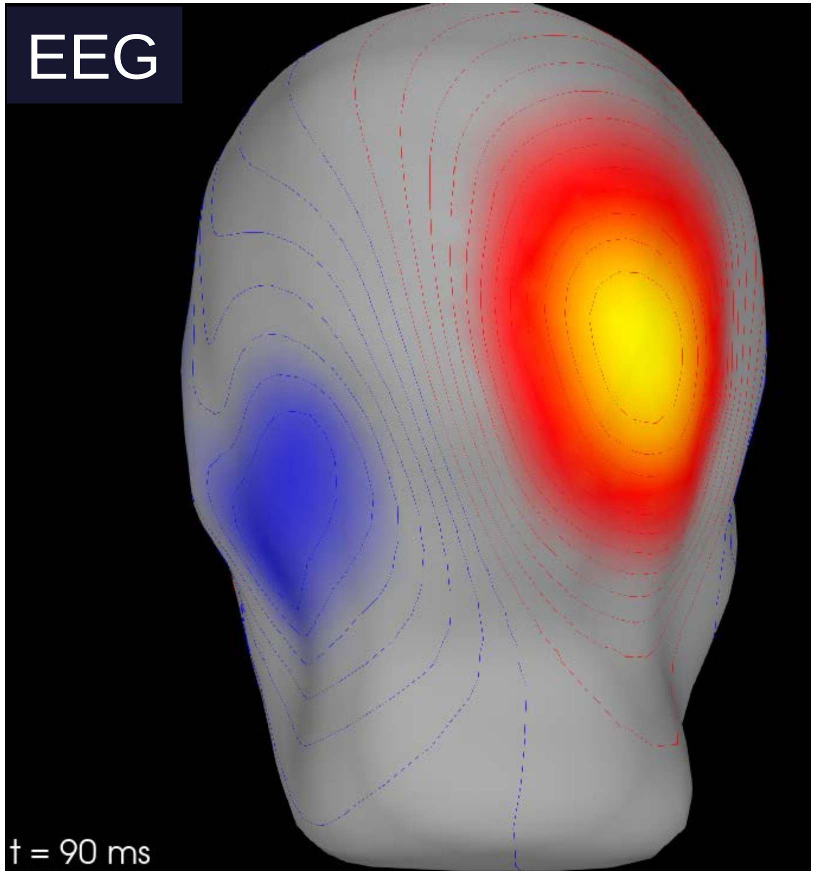


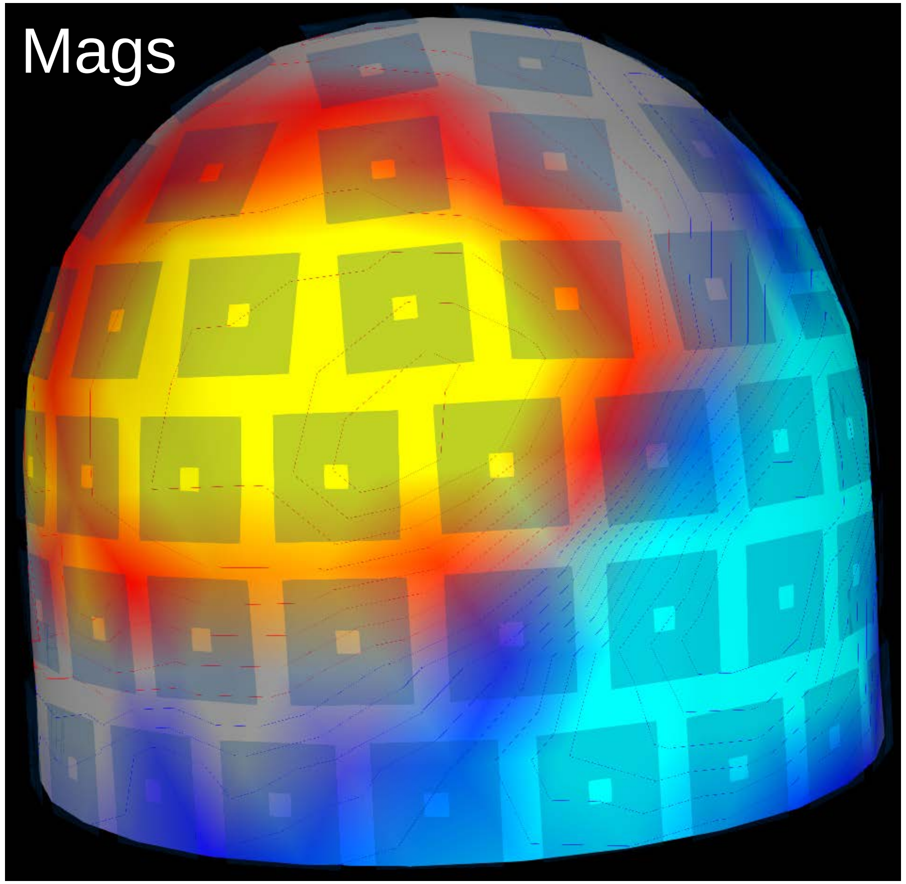


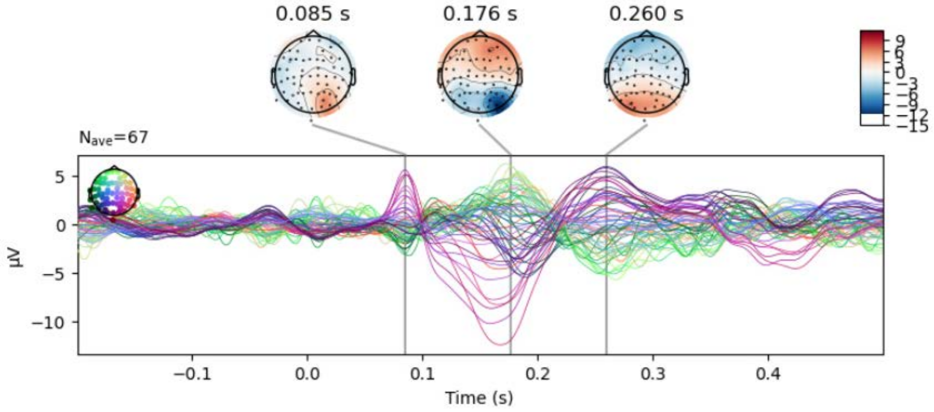
Example: Visually Evoked Activity ~100 ms

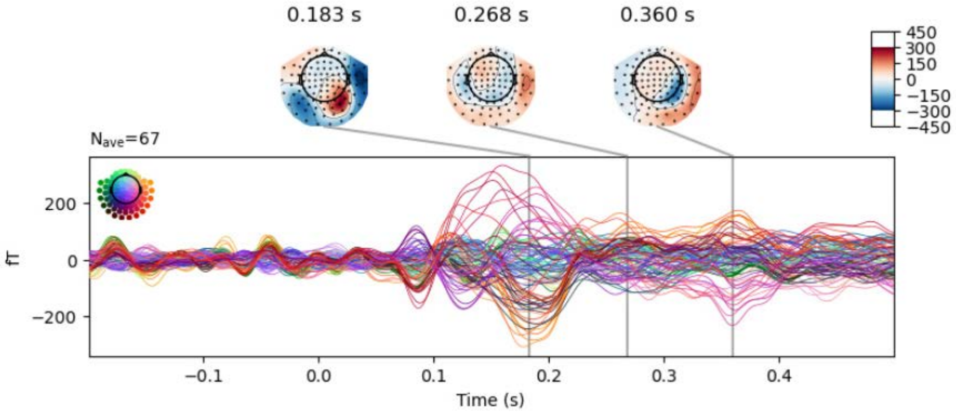
Checkerboard to left visual field









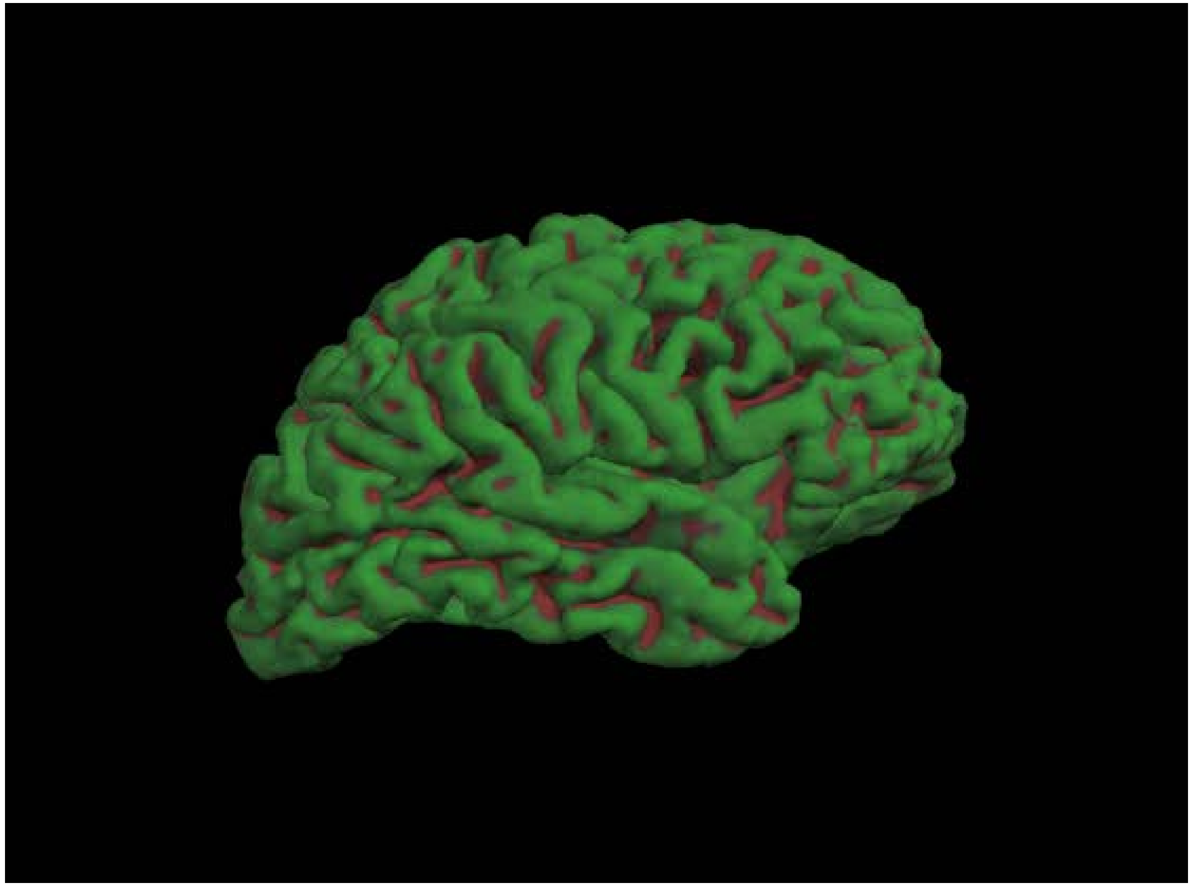


The Forward Problem and Head Modelling

Source Spaces

Source Space

Where active sources may be located, e.g. grey matter, 3D volume



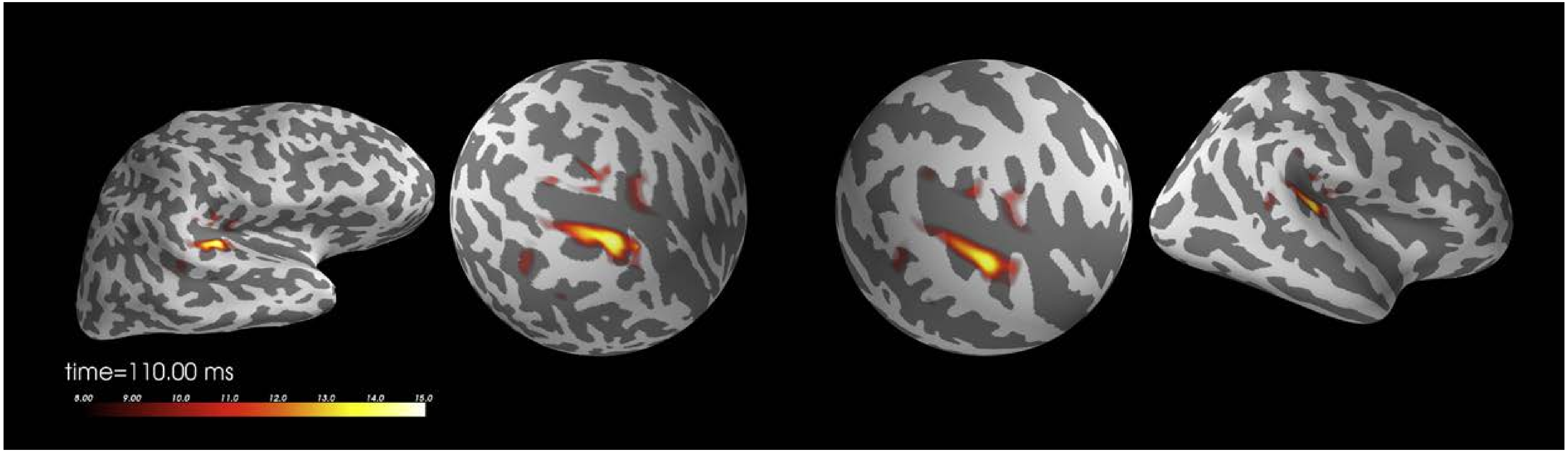
http://www.cogsci.ucsd.edu/~sereno/movies.html

Sometimes “standard head models” are used, when no individual MRIs available.

SPM uses the same “canonical mesh” as source space for every subjects, but adjusts it individually.

Normalising (Morphing) Cortical Surfaces

Morphing from individual to standard brain

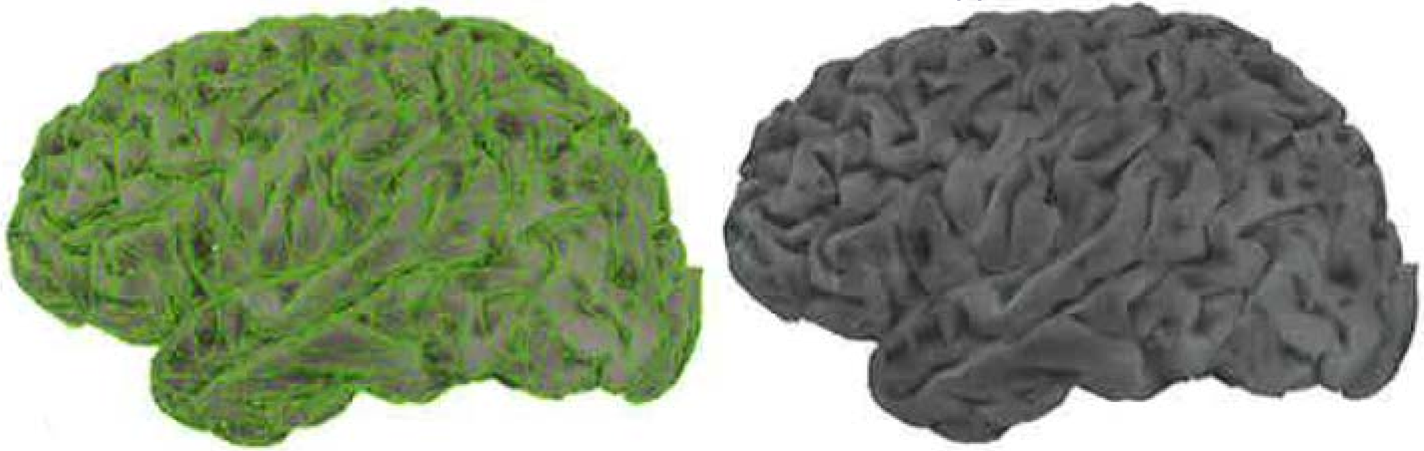


Gramfort et al., NI 2014

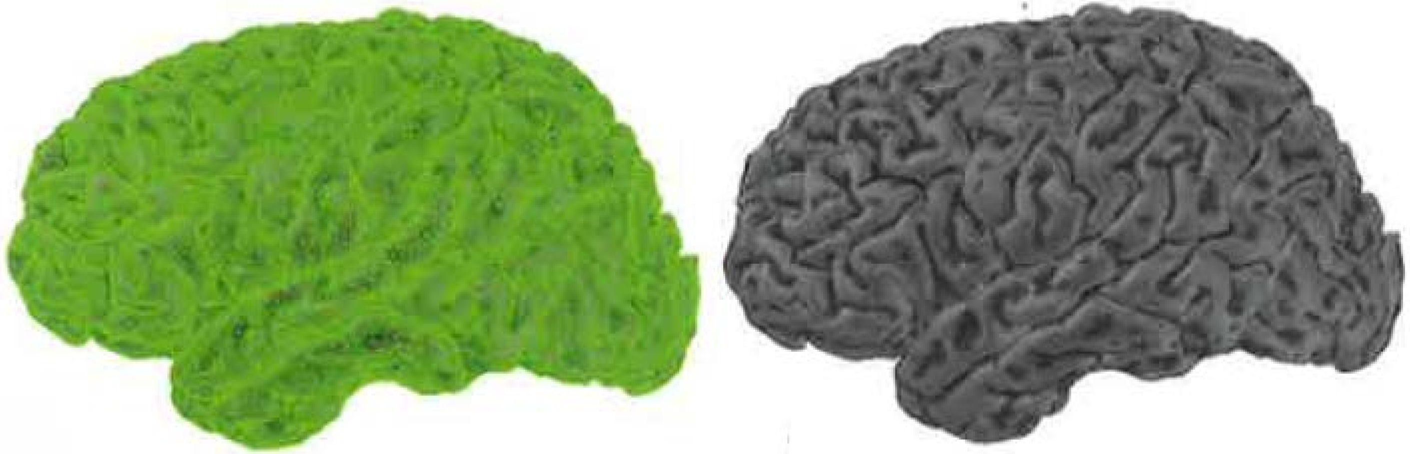
Spatial Sampling of Cortical Surfaces

10.034 vertices, 20.026 triangles of 10 mm^2 surface area

Sufficient for most EEG/MEG applications

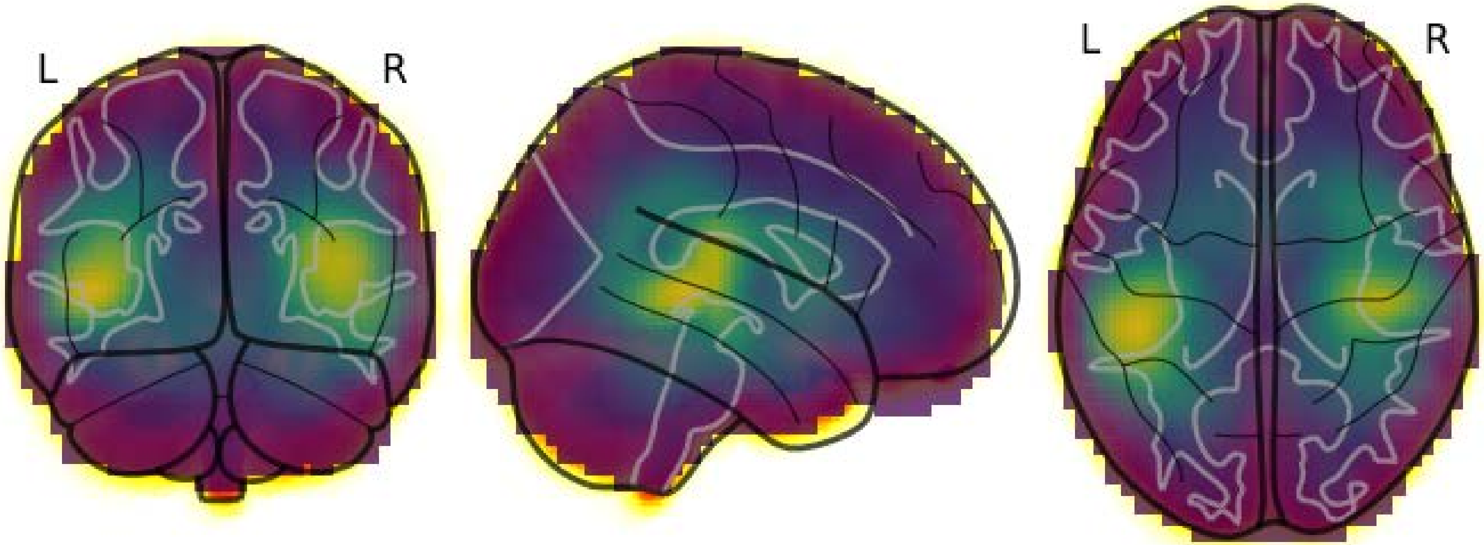


79.124 vertices, 158.456 triangles of 1.3 mm^2 surface area

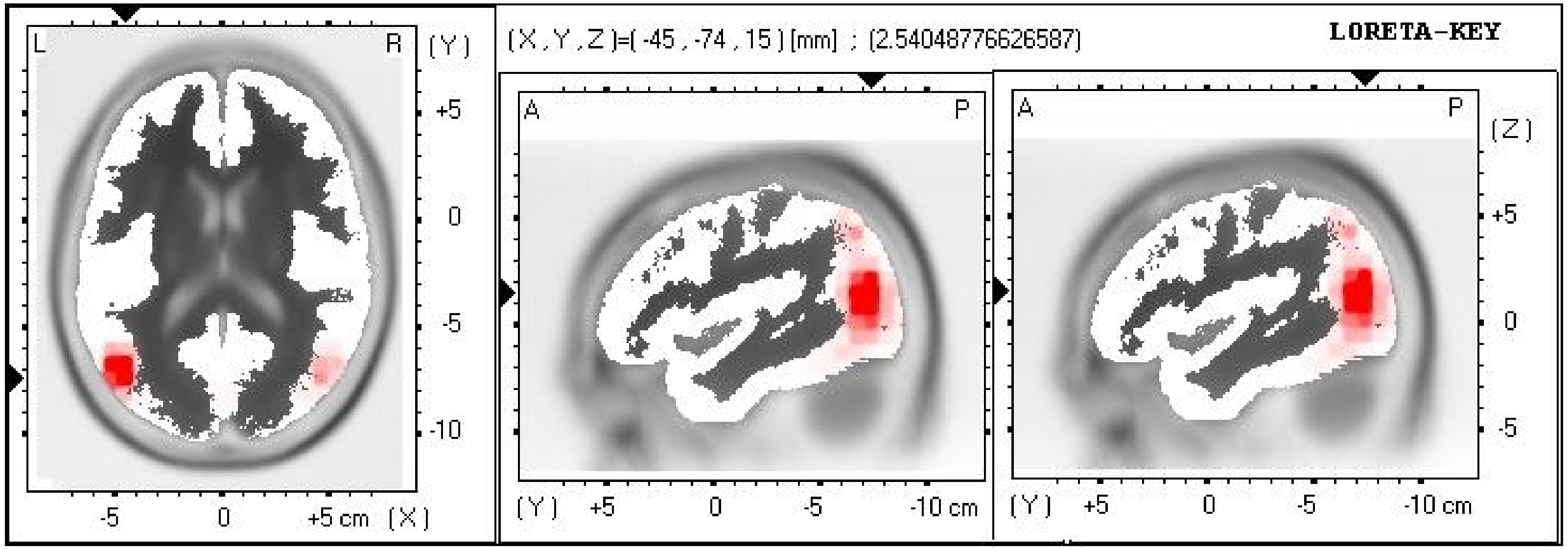


Baillet, chap. 5 in “MEG”, OUP 2010, Hansen/Kringelbach/Salmelin (edts.)

Volumetric Source Spaces Are Possible



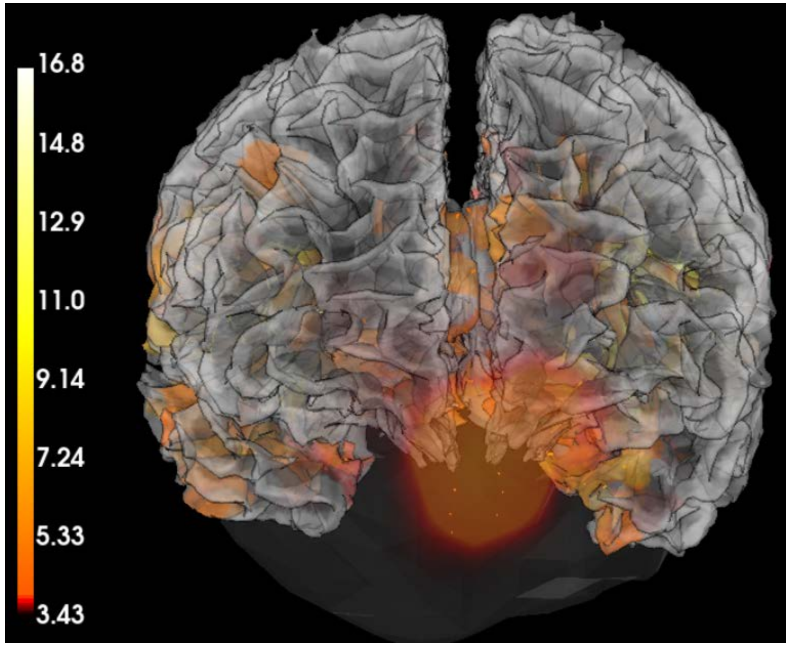
https://mne.tools/dev/auto_examples/inverse/morph_volume_stc.html



Pascqual-Marqui, PTRS-A 2011

Mixed Source Spaces

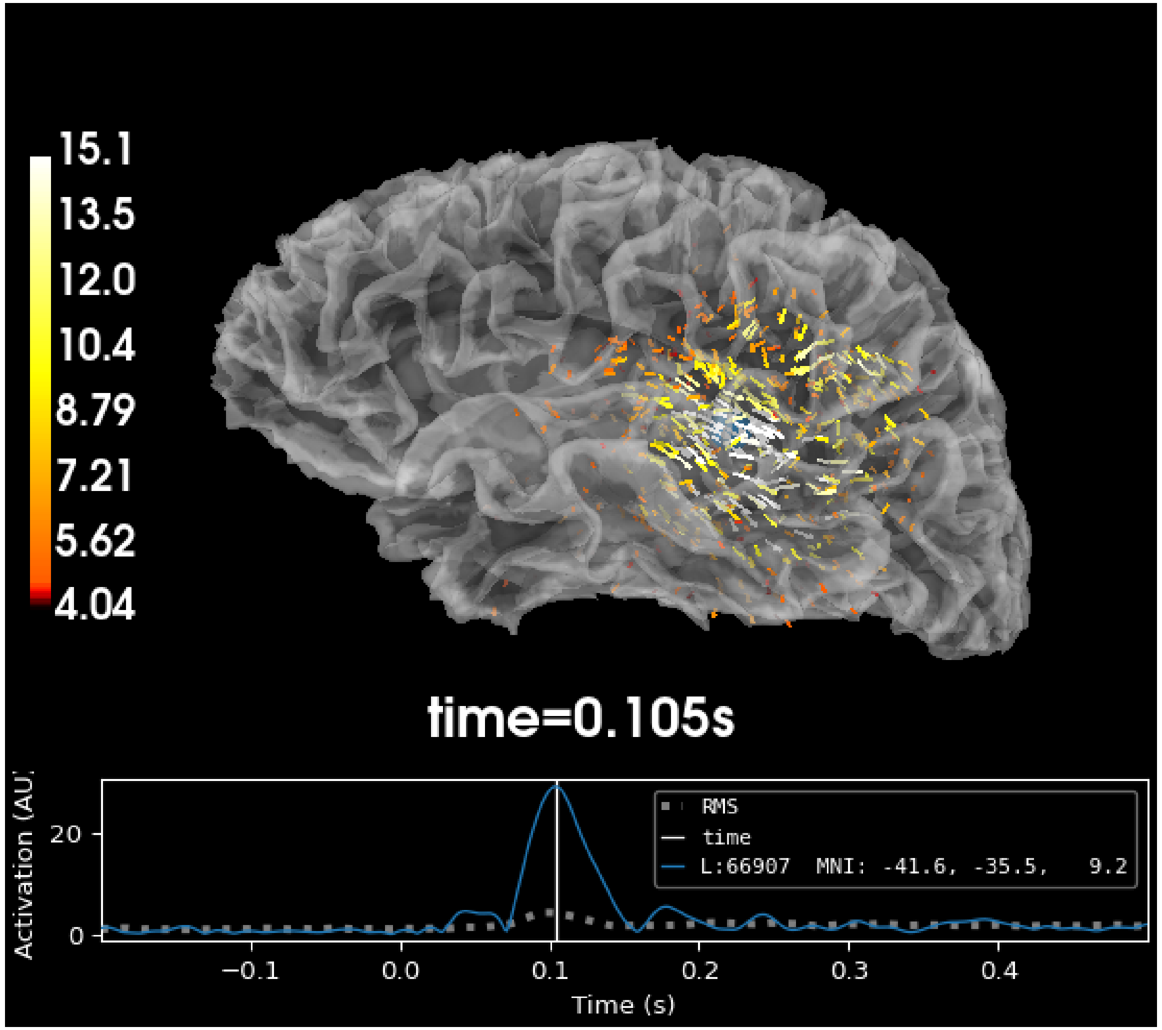
Cortical and Sub-Cortical Sources



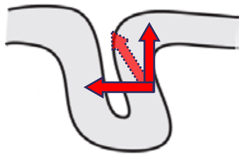
https://mne.tools/dev/auto_examples/inverse/mixed_source_space_inverse.html

Source Orientations

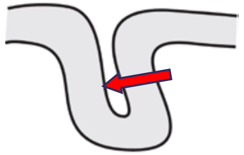
Current sources have a direction and/or orientation.



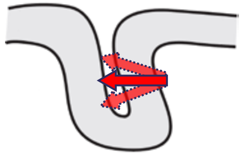
Constraints on source orientation:



“Free”



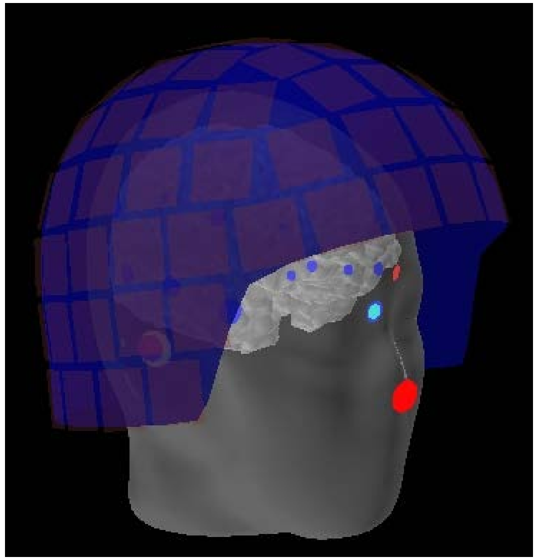
“Fixed”



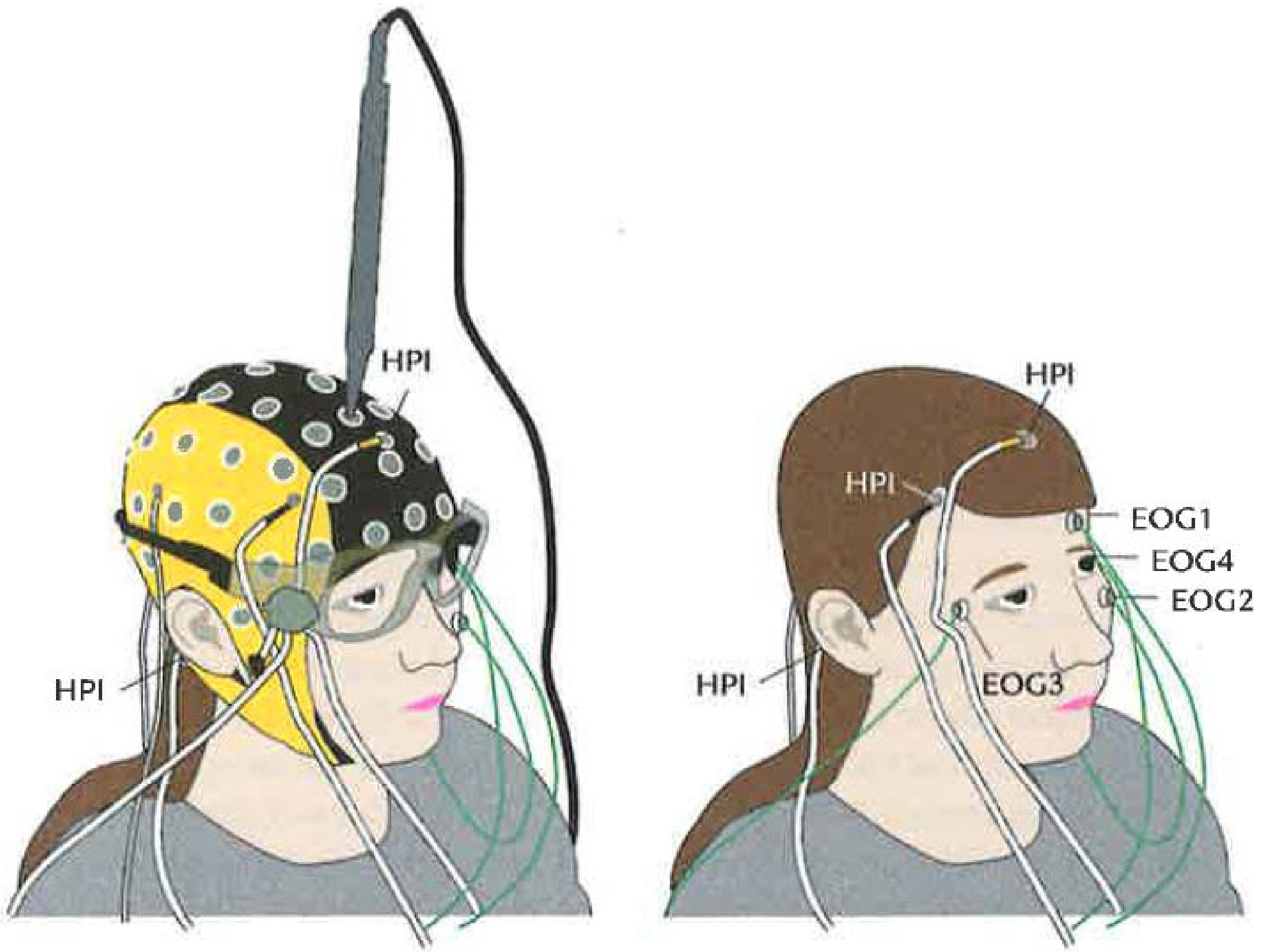
“Loose”

Coregistration of EEG/MEG and MRI Spaces

Coordinate
Transformation



Coregistration of EEG/MEG and MRI Spaces



MNE-Python tutorial: https://www.youtube.com/watch?v=ALV5qqMHLlQ

Hari & Puce, “MEG-EEG Primer”, OUP 2017

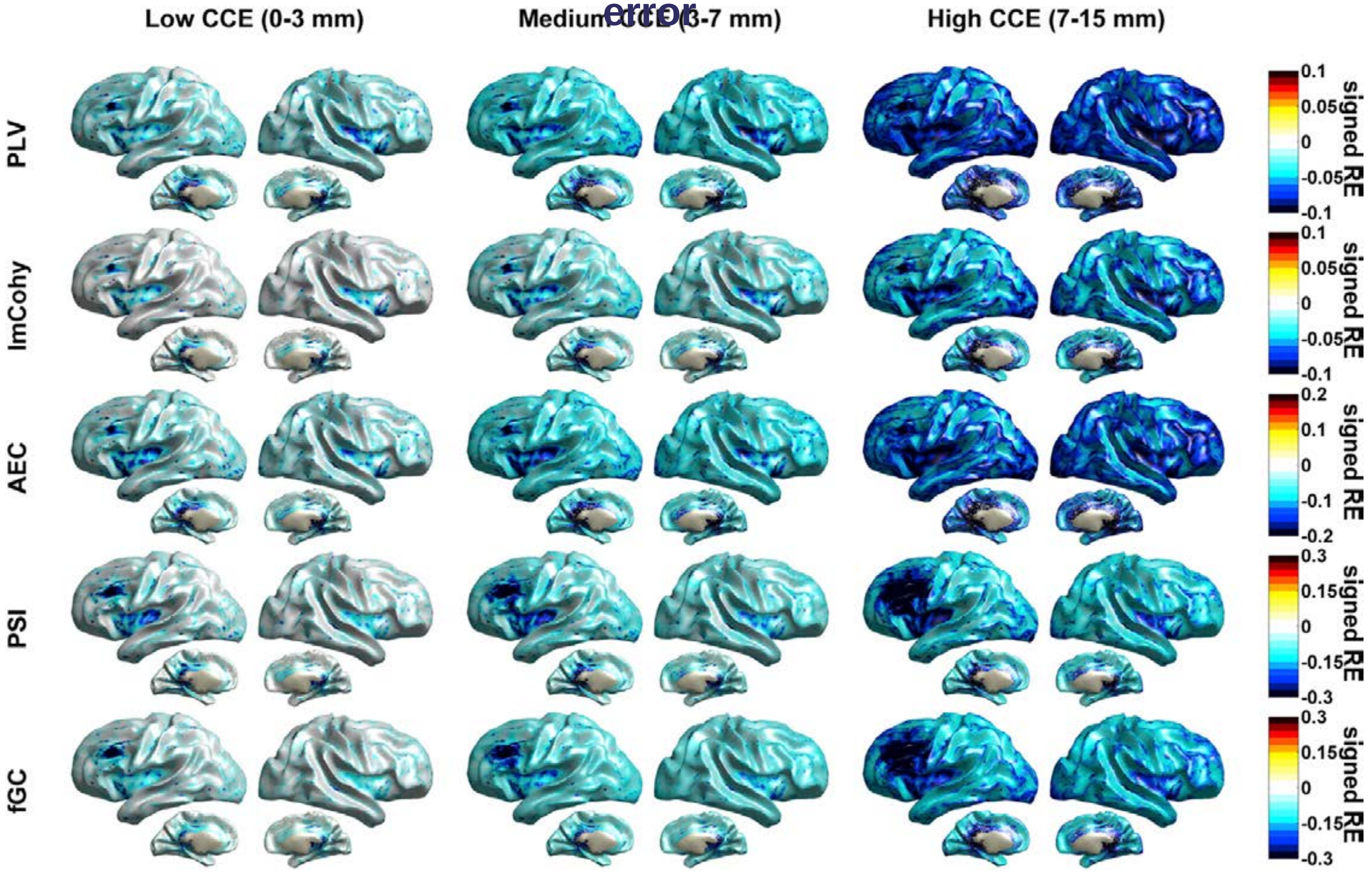
Accurate Coregistration Is Important

Coregistration errors affect the forward model, and therefore everything that follows.

For example, connectivity analysis:

3 levels of coregistration error

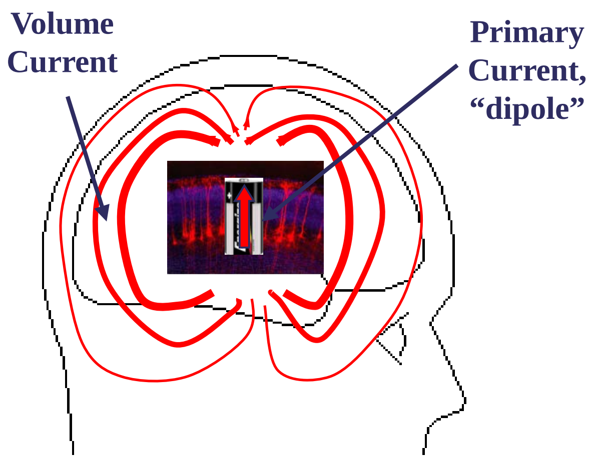
Functional Connectivity Metrics

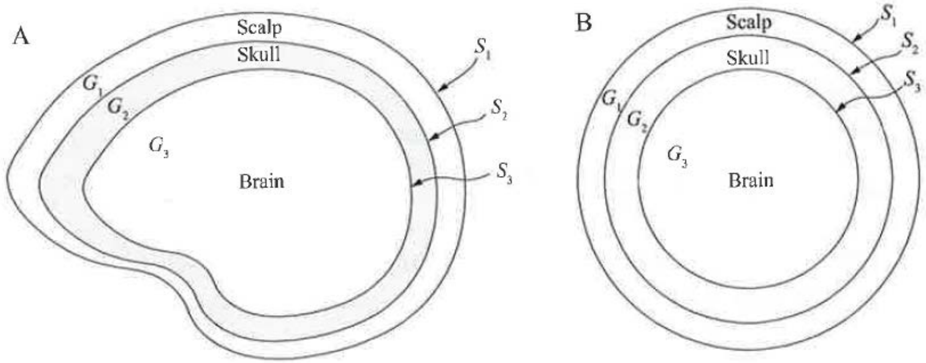


Chella et al., NI 2019, https://www.sciencedirect.com/science/article/pii/S1053811919303477

Head Models

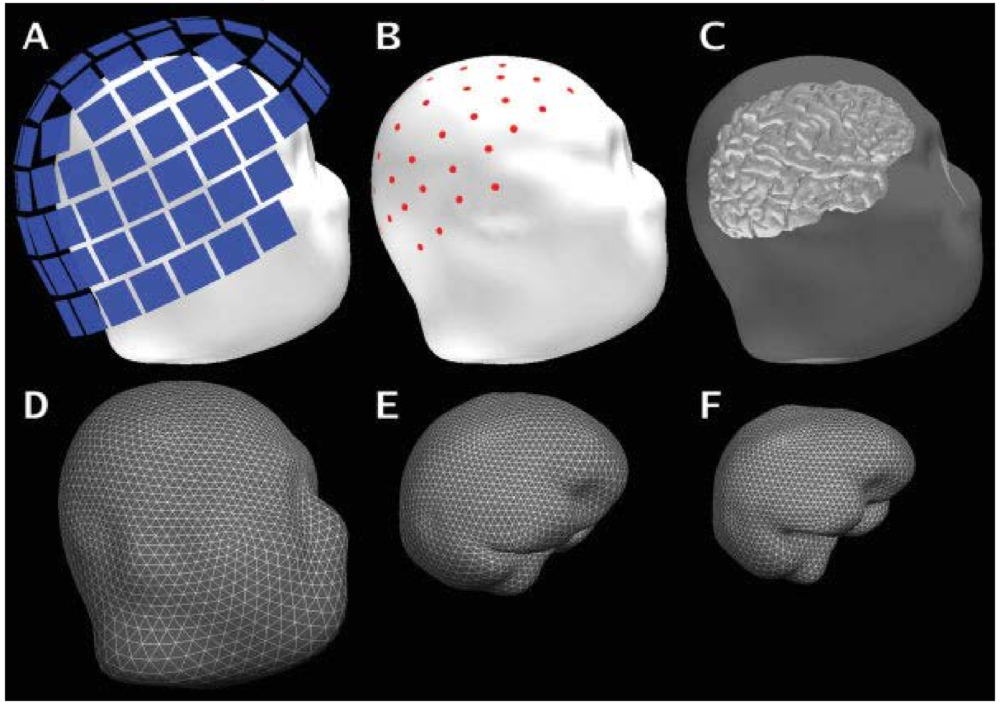
Boundary Element Model (BEM)





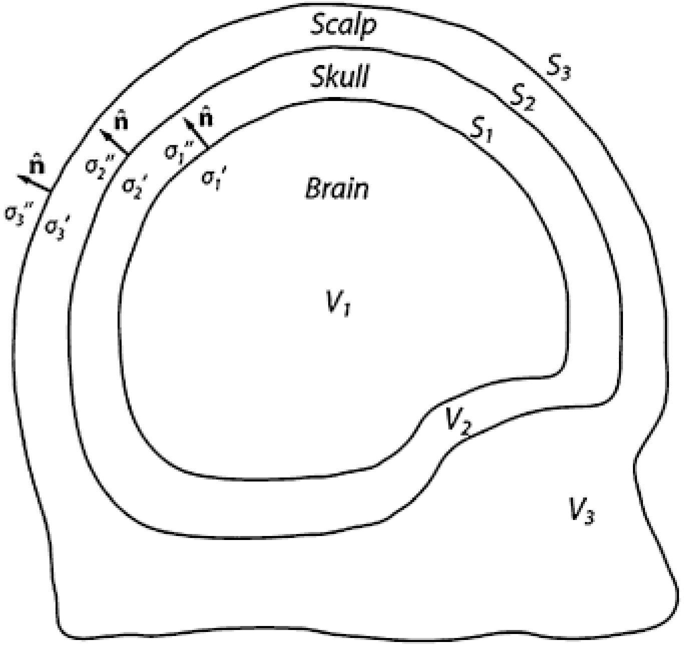
Ilmoniemi and Sarvas, “Brain Signals”, MIT 2019

Ingredients for a head model



Goldenholz et al., HBM 2009

Boundary Element Model (BEM)



Electric potential

$$\sigma(\mathbf{r})V(\mathbf{r}) = \frac{1}{4\pi}\sum_j \left(\sigma_j' - \sigma_j''\right)\int_{S_j} dS_j' \mathbf{n}(\mathbf{r}') \cdot \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} V(\mathbf{r}')$$

$$+ \frac{1}{4\pi}\int_V d^3r' \mathbf{J}^{\mathbf{p}}(\mathbf{r}') \cdot \frac{\mathbf{r} - \mathbf{r}'}{|\mathbf{r}' - \mathbf{r}|^3}.$$

Magnetic Field

$$\mathbf{B}^{\mathbf{P}}(\mathbf{r}) = \frac{\mu_0}{4\pi}\int_V \mathbf{J}^{\mathbf{P}}(\mathbf{r}') \times \nabla' \frac{1}{|\mathbf{r} - \mathbf{r}'|} d^3r',$$

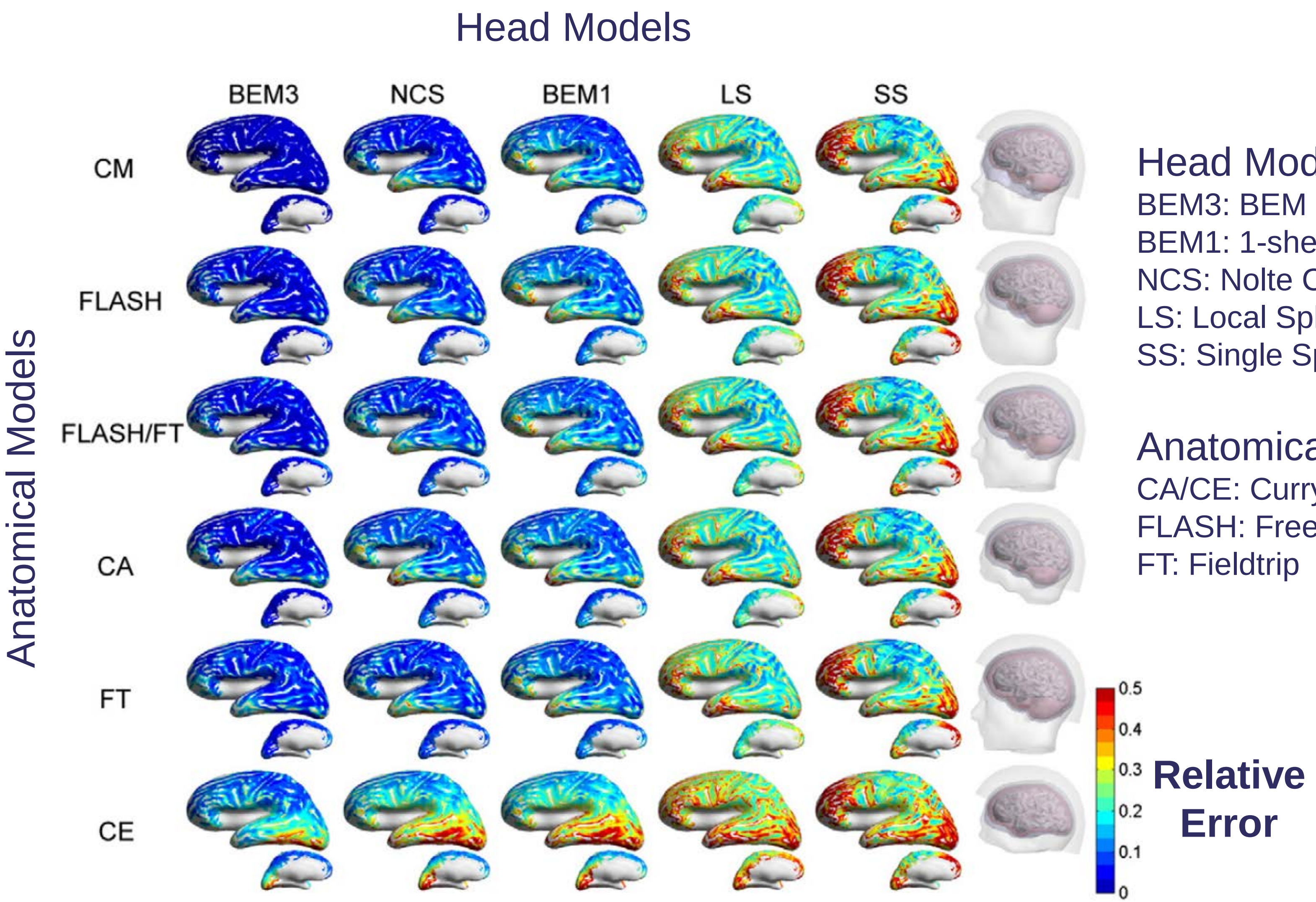
$$\mathbf{B}^{R}(\mathbf{r}) = -\frac{\mu_0}{4\pi}\sum_i \sigma_i \int_{V_i} \nabla' V(\mathbf{r}') \times \nabla' \frac{1}{|\mathbf{r} - \mathbf{r}'|} d^3r',$$

Heller & Volegov, in Magnetoencephalography by Supek & Aine (edts), Springer 2019

- Volume currents depend on conductivity distribution within the whole head volume.
- EEG measurements on the scalp are the result of volume currents, and are strongly affected by head geometry.
- MEG measurements are the sum of magnetic fields from primary and volume currents, but the magnetic fields of currents close to the source are much stronger than at larger distances.

➢ Thus, MEG signals are less affected by head geometry (e.g. skull and scalp). We usually only use one compartment (inner skull) for MEG (unless in combination with EEG).

The Effect of Head Model Accuracy for MEG



Head Models:

BEM3: BEM 3-shell
BEM1: 1-shell
NCS: Nolte Corrected Sphere
LS: Local Sphere
SS: Single Sphere

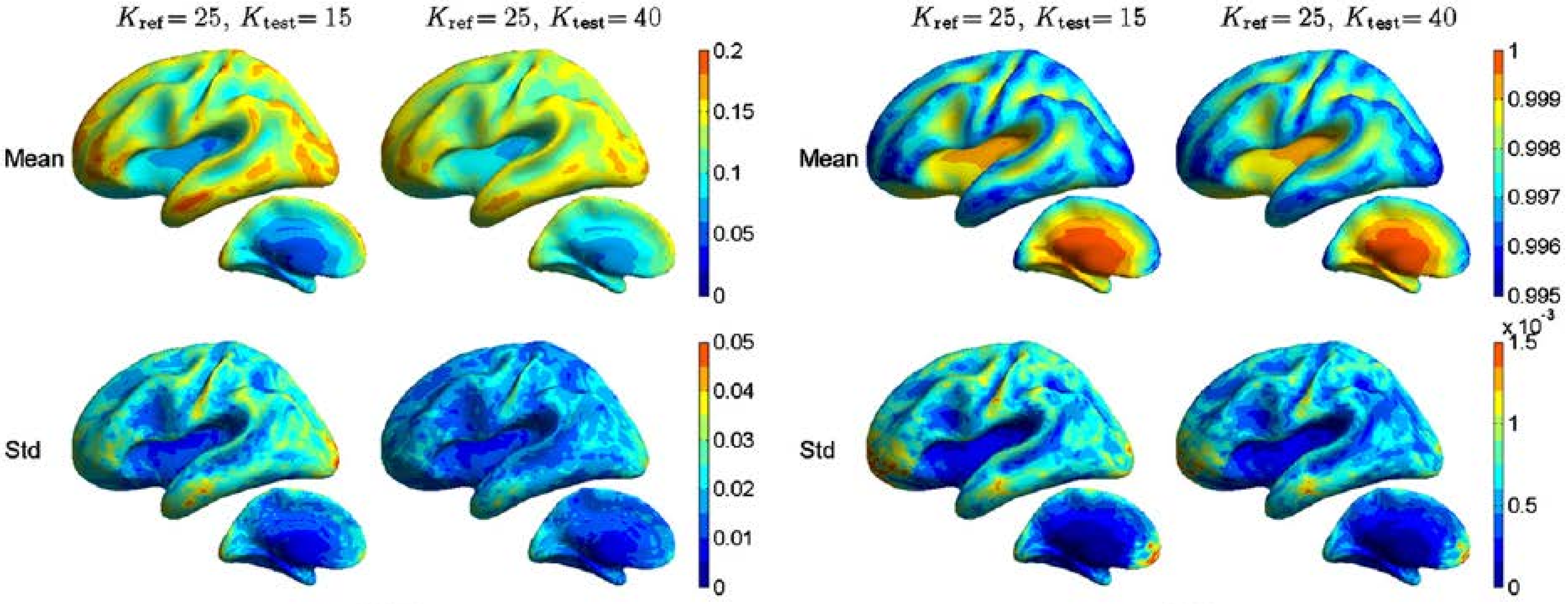
Anatomical Models:

CA/CE: Curry
FLASH: Freesurfer
FT: Fieldtrip

Stenroos, Neuroimage 2014, https://pubmed.ncbi.nlm.nih.gov/24434678/

Boundary Element Models Are Relatively Robust Against Conductivity Errors

underestimated conductivity | overestimated conductivity | underestimated conductivity | overestimated conductivity



Relative Error

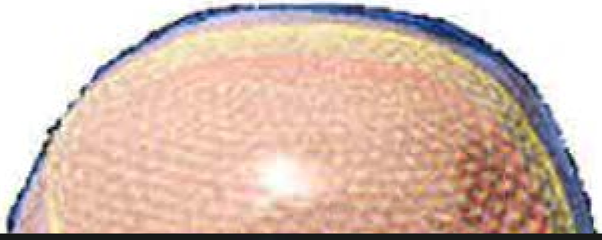
Correlation Coefficient

Stenroos & Hauk, NI 2013
https://pubmed.ncbi.nlm.nih.gov/23639259/

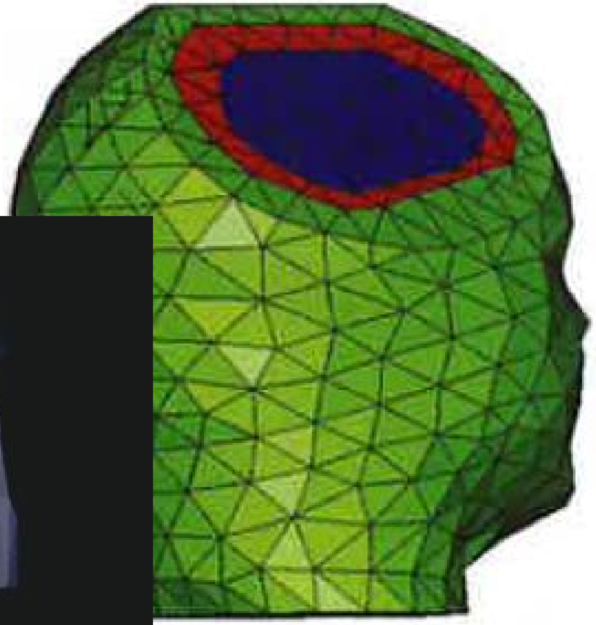
Head Models With Different Levels of Detail

Spheres

Boundary Element Model
(BEM)



Finite Element Model
(FEM)



Baillet, chap. 5 in “MEG”, OUP 2010, Hansen/Kringelbach/Salmelin (edts.)

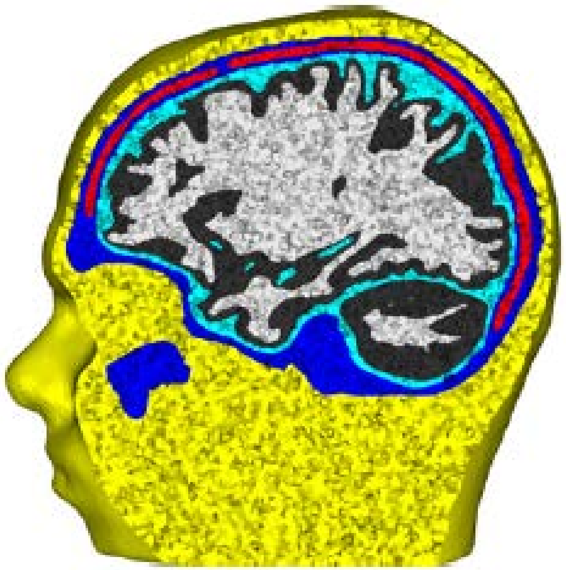
Finite Element Models (FEMs)

The use of 3-layer (brain, skull, scalp) BEM models based on individual MRI images is state-of-the-art for EEG/MEG source estimation.

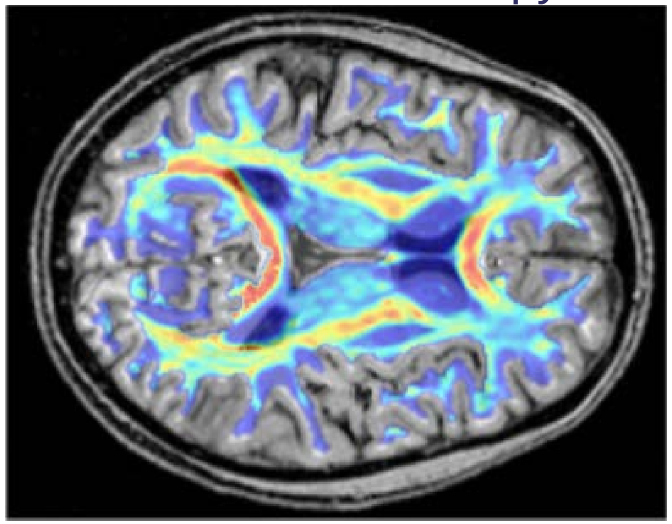
For MEG-only, single shell BEMs and local/corrected sphere models can provide reasonable approximations.

But heads are more complex:

White Matter
Gray Matter
CSF
Skull
Compacta
Skull
Spongiosa
Skin



Fractional Anisotropy



Vorwerk et al., NI 2014

It is not obvious how to translate this into more accurate estimate for conductivity distributions.

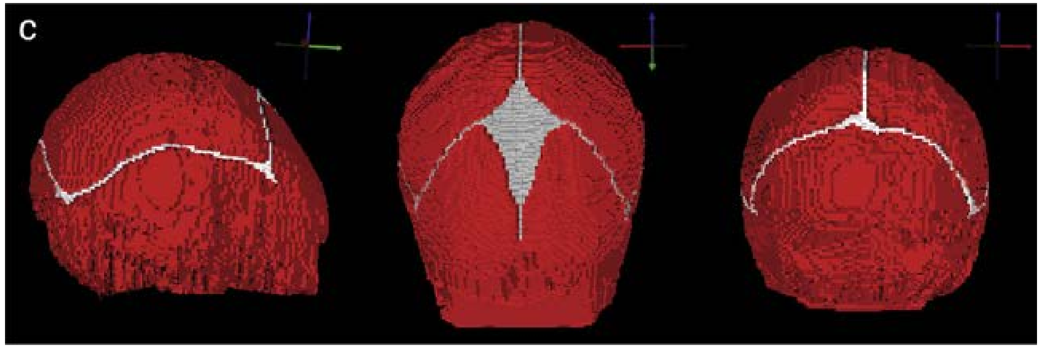
Conductivities Of Tissues Can Only Be Approximated

Table 2 Isotropic conductivity values of single tissue types used in human head volume conductor modeling

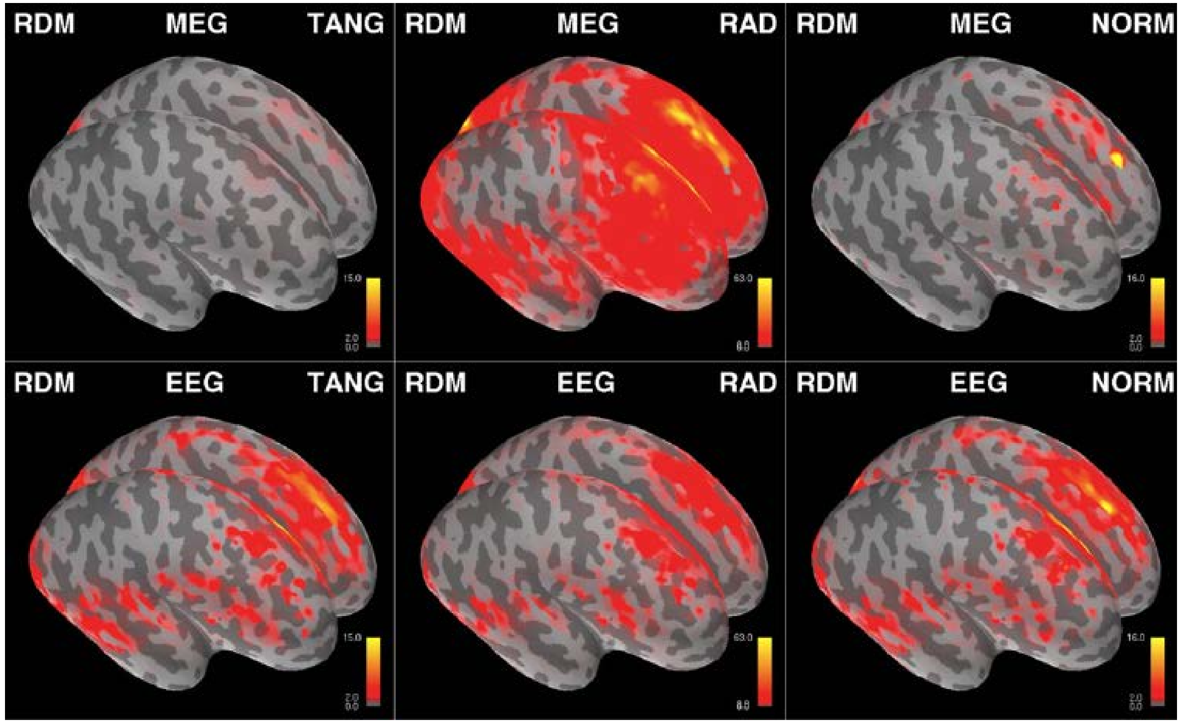
Tissue	Conductivity in S/m	Reference
Brain gray matter	0.45	Logothetis et al. 2007
Brain white matter	0.1	Akhtari et al. 2010
Spinal cord and cerebellum	0.16	Haueisen et al. 1995
Cerebrospinal fluid	1.79	Baumann et al. 1997
Hard bone (compact bone)	0.004	Tang et al. 2008
Soft bone (spongiform bone)	0.02	Akhtari et al. 2002
Blood	0.6	Gabriel et al. 2009
Muscle	0.1	Gabriel et al. 1996, 2009
Fat	0.08	Gabriel et al. 2009
Eye	1.6	Pauly and Schwan 1964; Lindenblatt and Silny 2001
Scalp	0.43	Geddes and Baker 1967
Soft tissue	0.17	Haueisen et al. 1995
Internal air	0.0001	Haueisen et al. 1995

Haueisen & Knösche, Chapter of “Magnetoencephalography” by Supek & Aine (edts.)

Infant Skulls – Fontanelles and Sutures

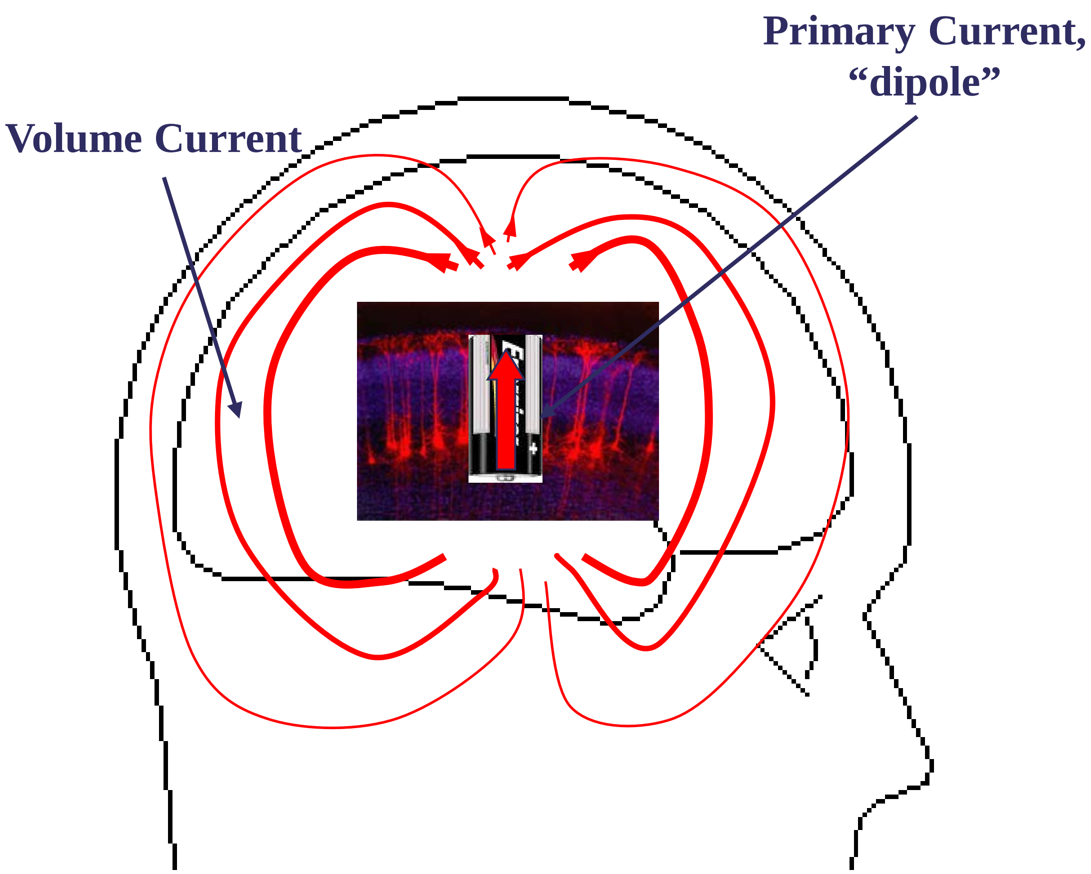


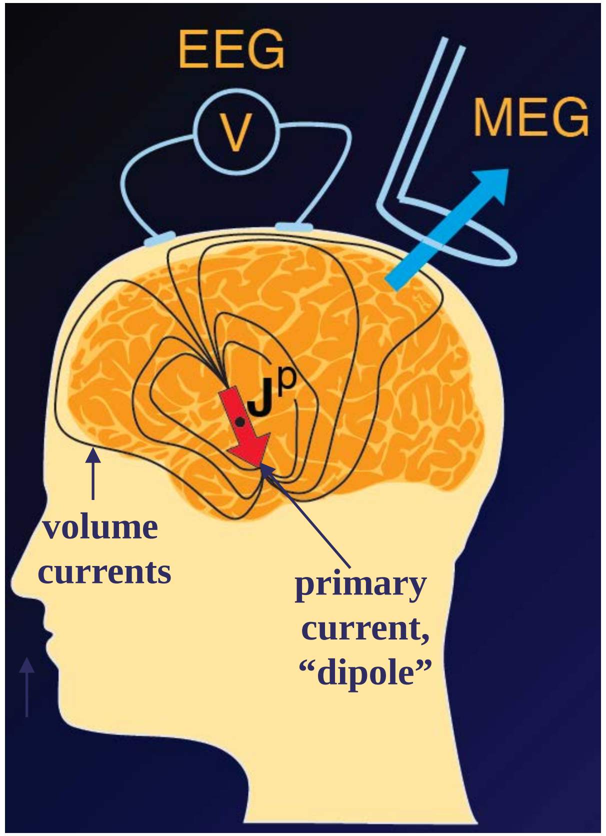
Relative error between models with and without fontanelles/sutures



Lew et al., NI 2013

Different Sensitivities of EEG and MEG





http://www.nmr.mgh.harvard.edu/meg/pdfs/talks/

All effects are instantaneous.

Volume currents affect both EEG and MEG –

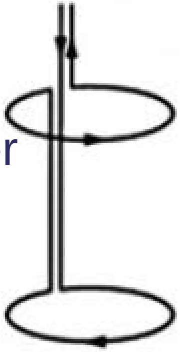
but EEG more than MEG

Different Sensors and their Sensitivities (Leadfields)

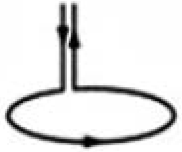
Leadfields are “sensitivity profiles” of individual sensors.

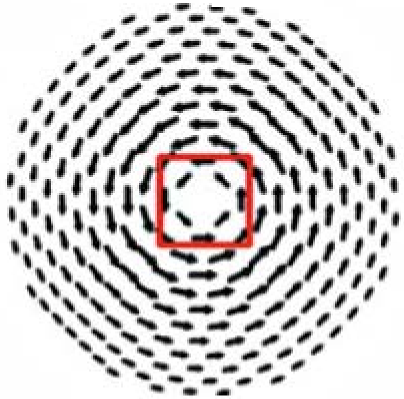
Each sensor is maximally sensitive to sources oriented along the arrows, and insensitive to sources perpendicular to the arrows.

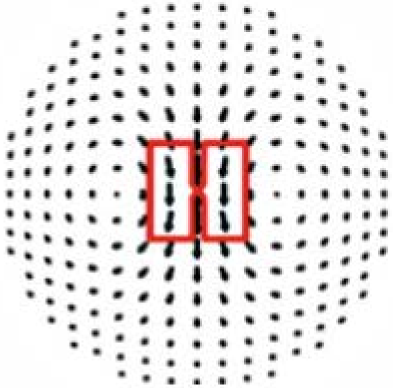
Axial Gradiometer



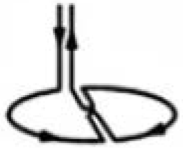
Magnetometer

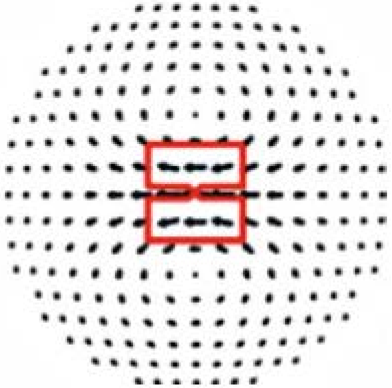




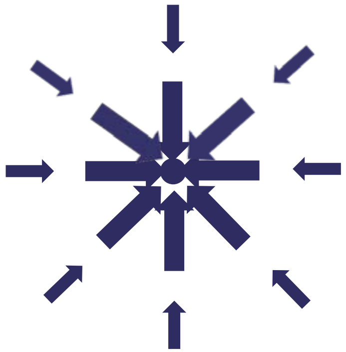


Planar Gradiometer(s)

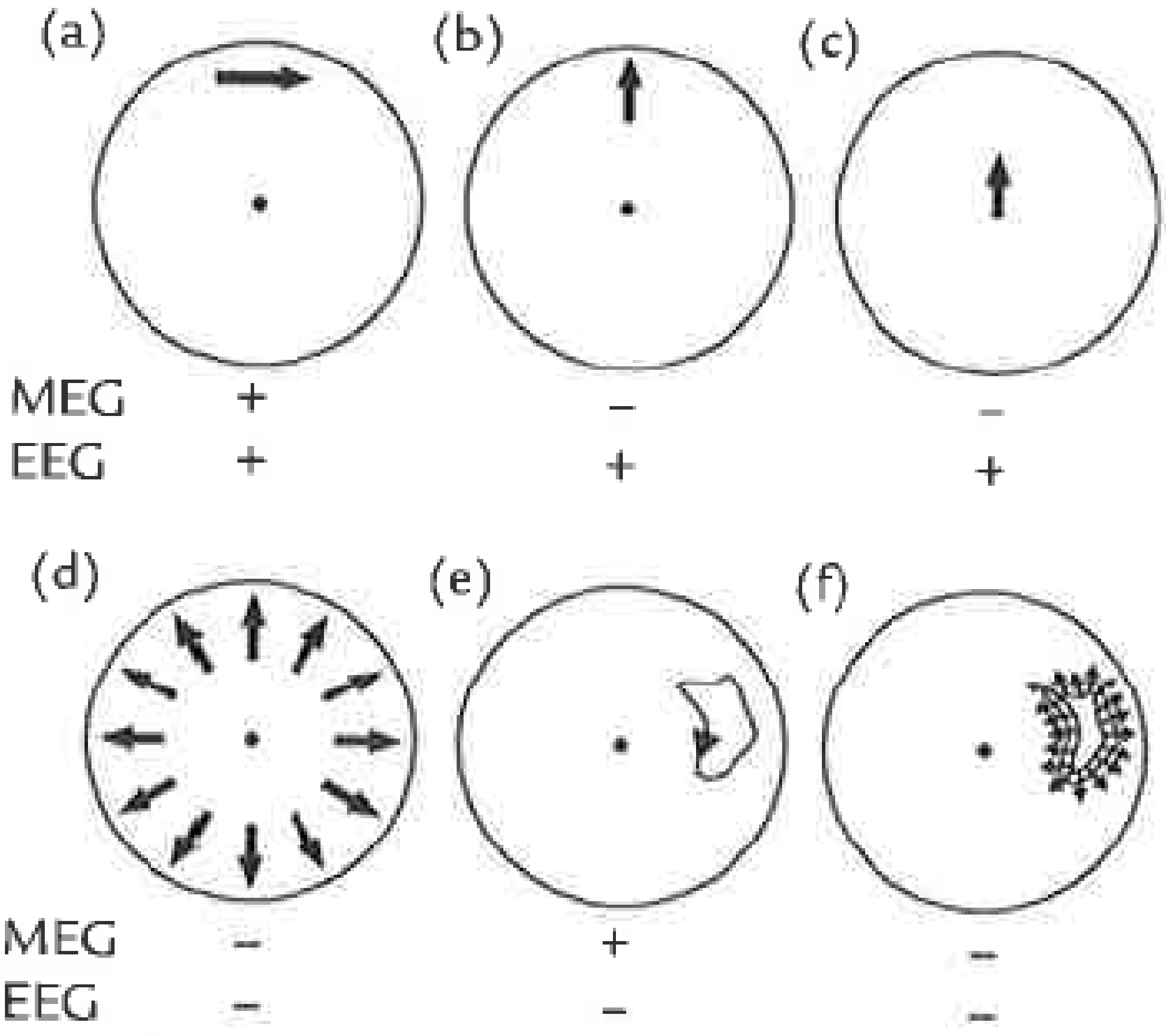




EEG Electrode



EEG and MEG Are Differentially Sensitive To Radial and Tangential Sources



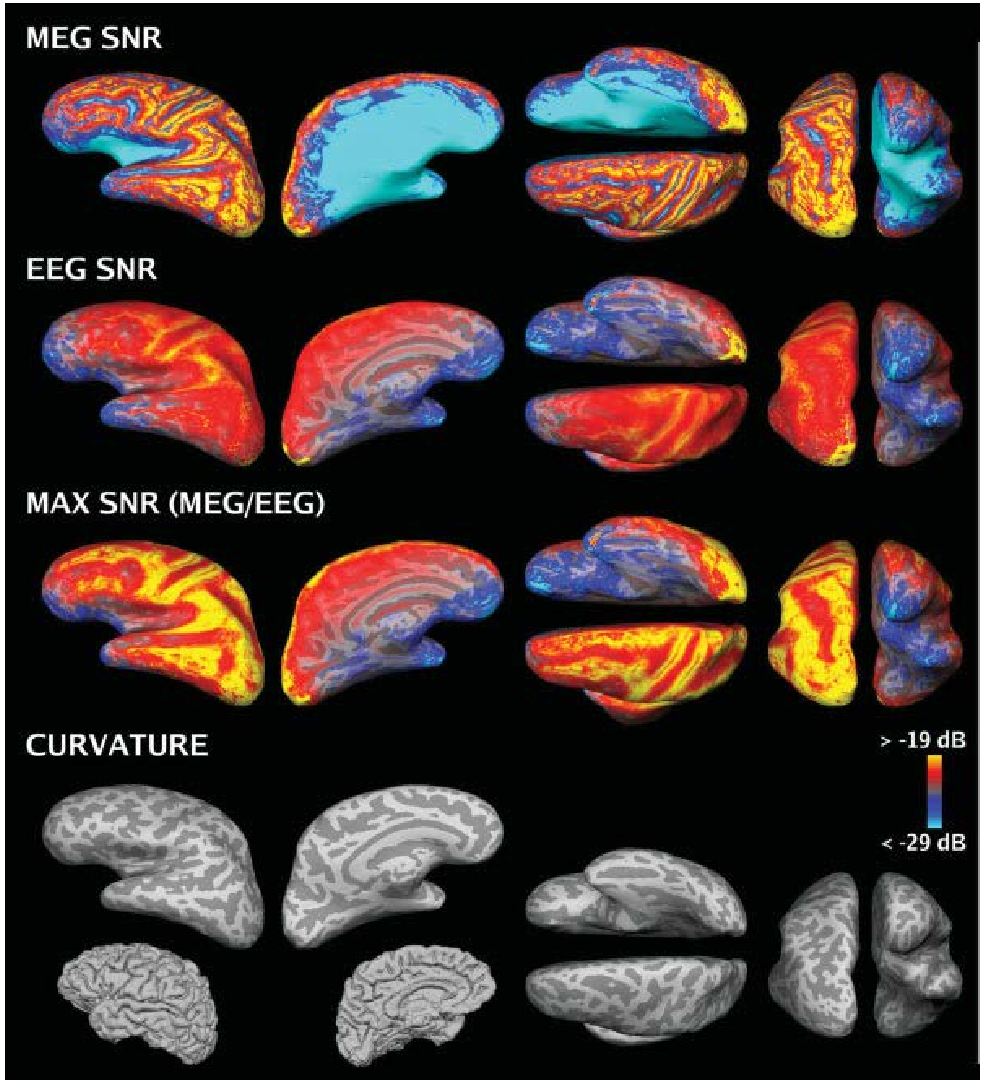
MEG is relatively insensitive to radial currents, and therefore also to deep currents.

Some complex source distributions may not produce EEG or MEG signals.

MEG-EEG Primer, Hari & Puce, OUP 2017

Sensitivity Maps

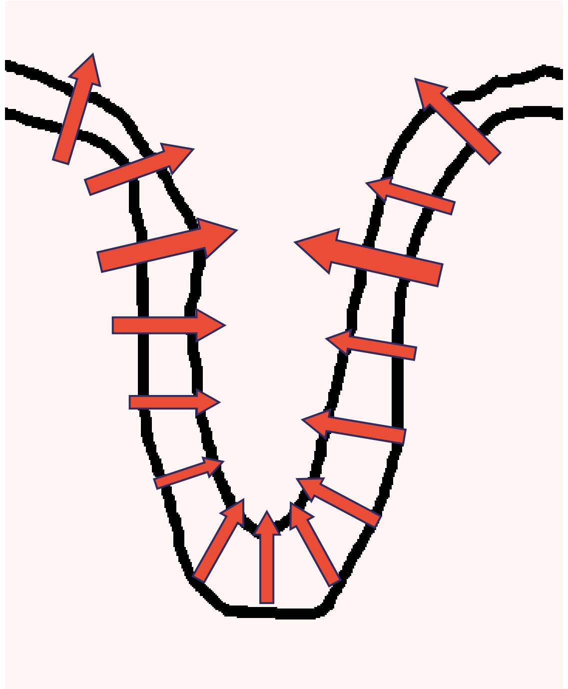
Sensor type, coverage and distance to sources strongly affect sensitivity and spatial resolution

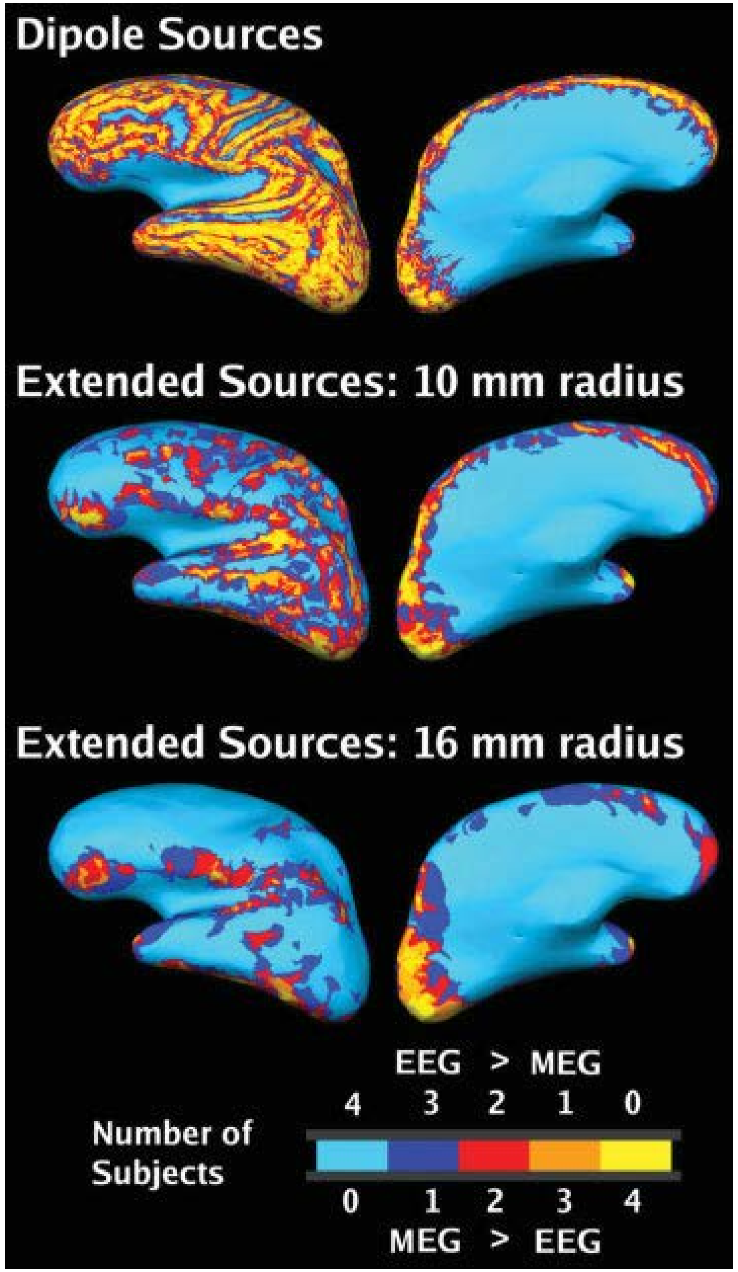


Goldenholz et al., HBM 2009
https://pubmed.ncbi.nlm.nih.gov/18465745/

MEG Is Less Sensitive To Spatially Extended Sources Than EEG

Distributed source around sulcus





Goldenholz et al., HBM 2009
https://pubmed.ncbi.nlm.nih.gov/18465745/

Conclusion – Head Modelling

3-compartment BEM models are currently state-of-the-art for EEG/MEG source estimation.

Single-shell approximations are still common for MEG.

More detailed head models may increase accuracy, but require more accurate data and information, such as accurate MRI segmentations and conductivity values. (see e.g. Vorwerk et al., BioMeg Eng Online 2018) for Fieldtrip FEM pipeline)

There is no right or wrong, there are only different approximations – know your limits.

Fixing Head Models

https://mne.tools/stable/auto_tutorials/forward/80_fix_bem_in_blender.html

Thank you