MRC Cognition and Brain Sciences Unit
UNIVERSITY OF CAMBRIDGE

EEG/MEG 2:

Head and Forward Modelling

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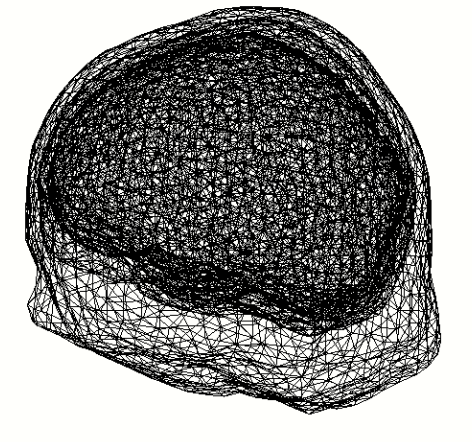
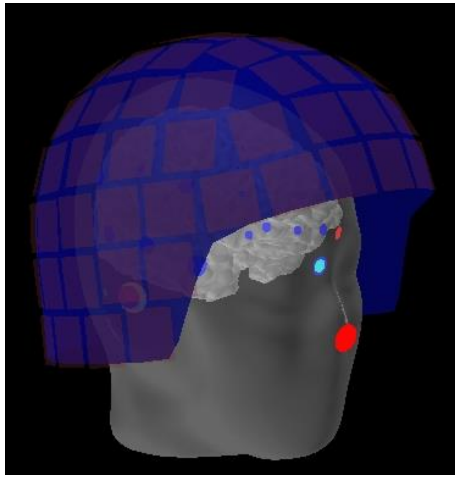
COGNESTIC 2023

Ingredients for Source Estimation

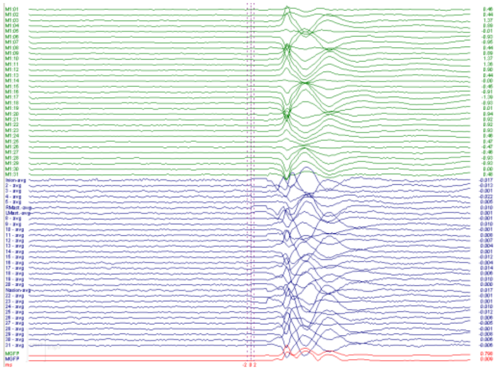
Volume Conductor/
Head Model



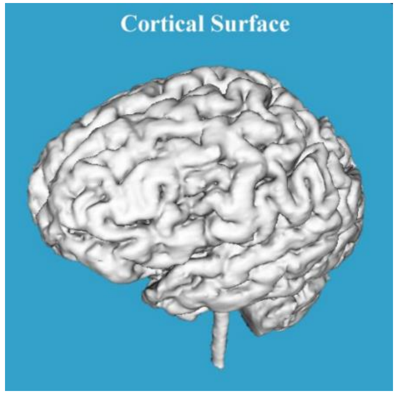
Coordinate
Transformation



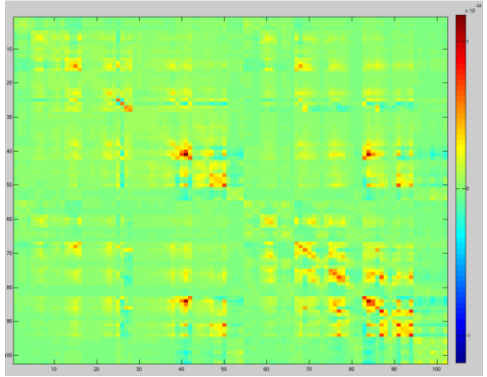
MEG data



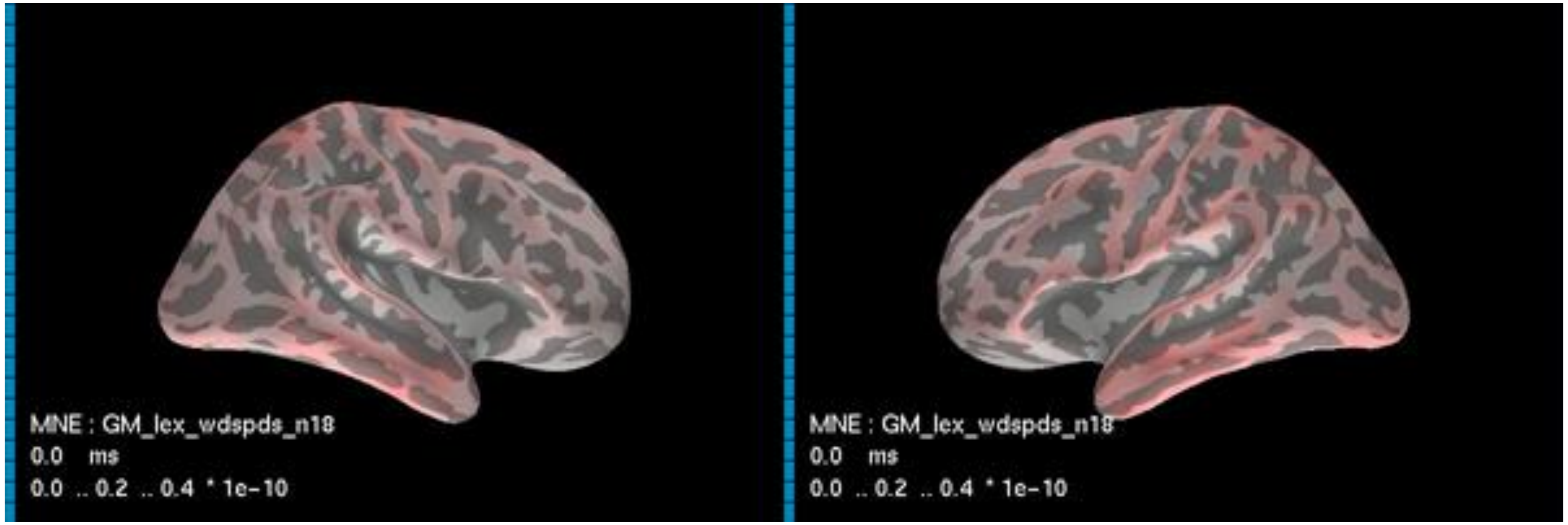
Source Space



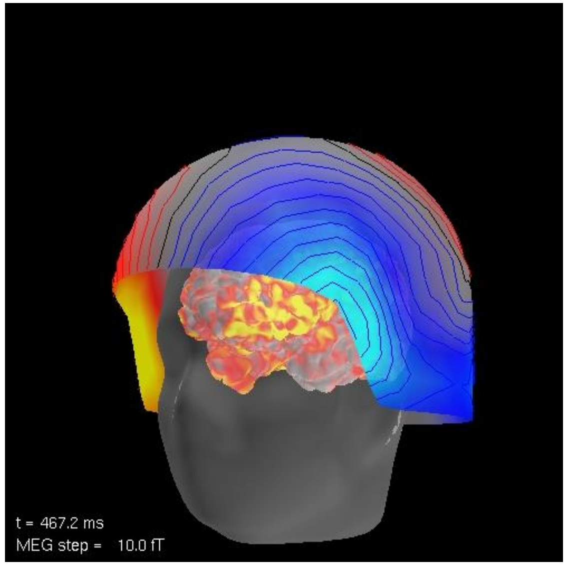
Noise/Covariance Matrix



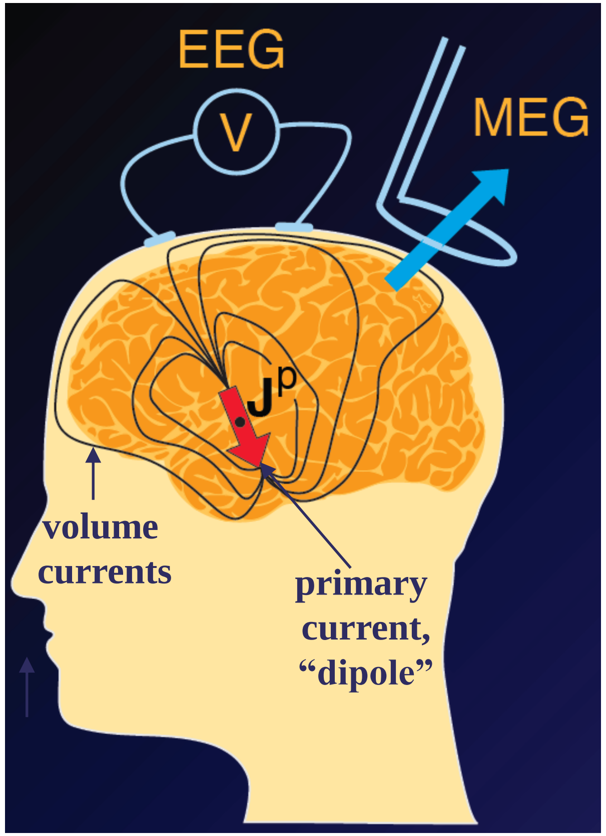
Our Goal: Spatio-Temporal Brain Dynamics
“Brain Movies”



The EEG/MEG Forward Problem

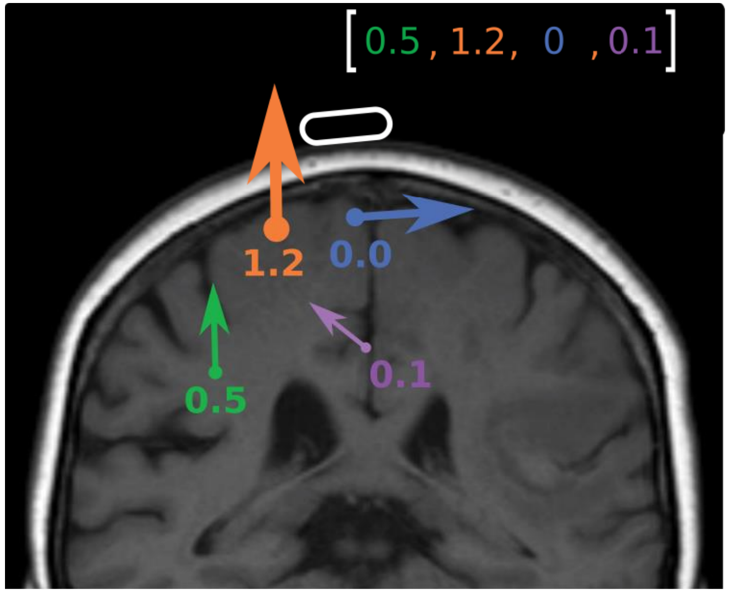


EEG/MEG measure the primary sources indirectly



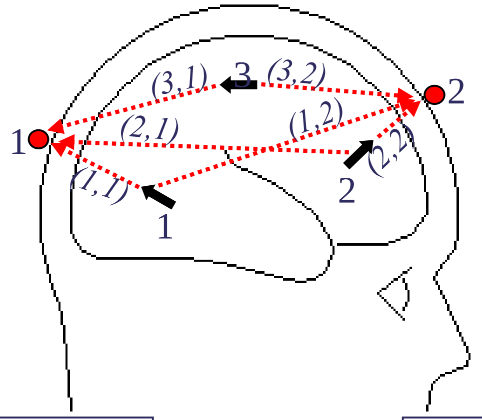
Sensors are differently sensitive to different sources

"Leadfield"



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

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



data "leadfield" dipoles

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

?

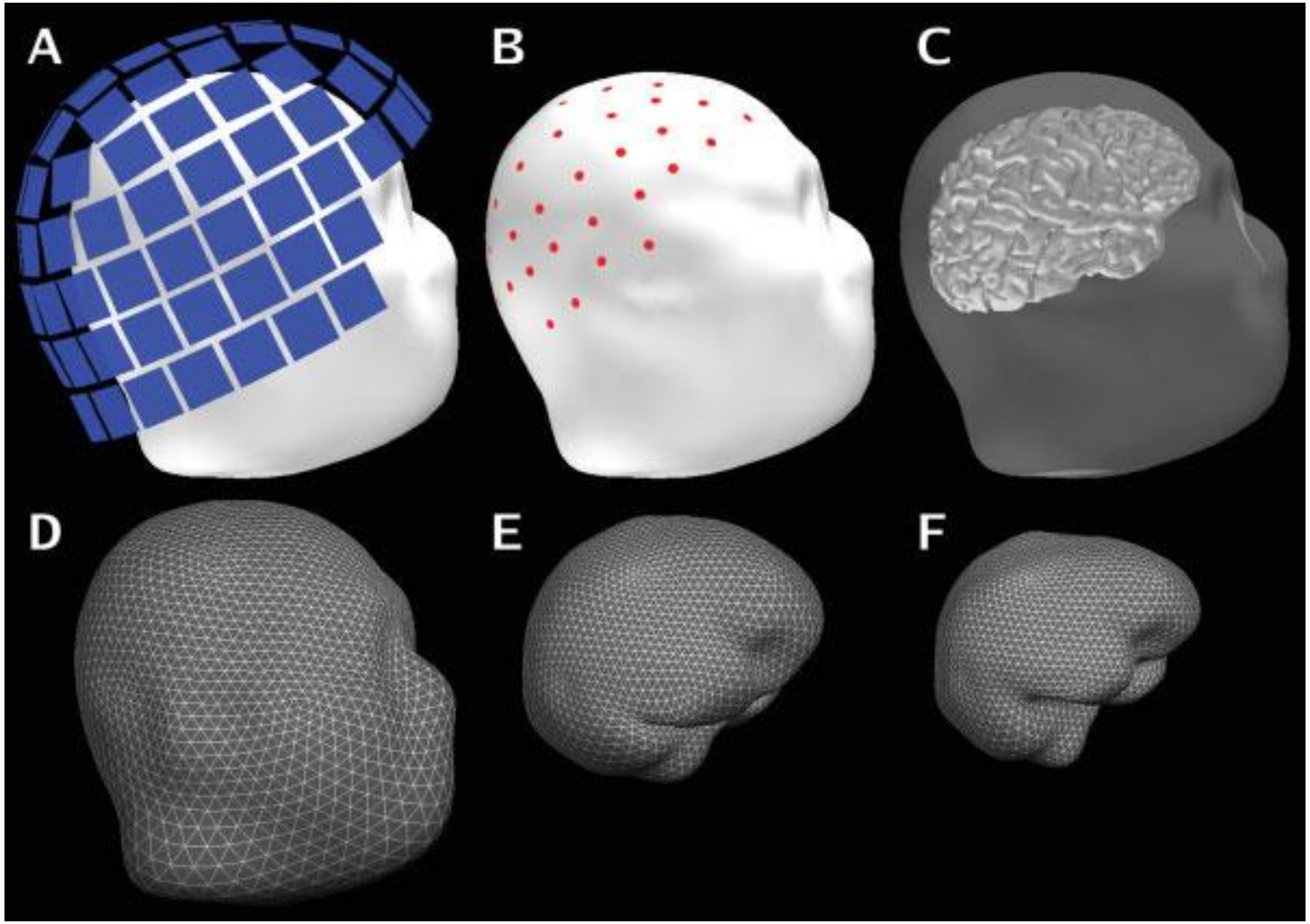
inversion

Inverse Operator

dipoles inverse data

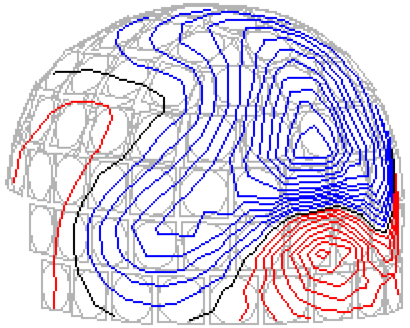
$$\begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix} = \begin{pmatrix} 1.5034 & 0.1241 \\ 0.2483 & 0.9379 \\ 0.8276 & -0.2069 \end{pmatrix} * \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$$

Ingredients for a head model

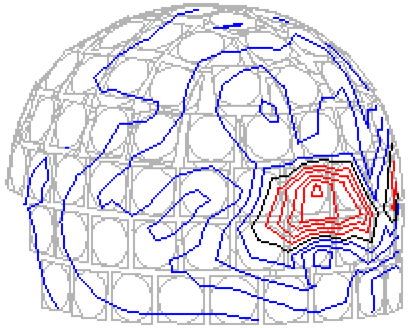


Goldenholz et al., HBM 2009
https://pubmed.ncbi.nlm.nih.gov/18465745/

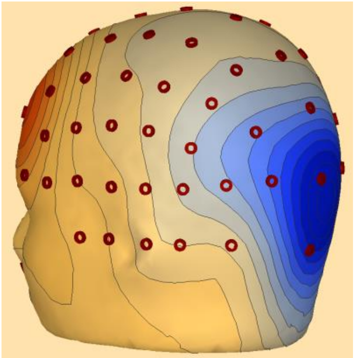
Example: Visually Evoked Activity ~100 ms



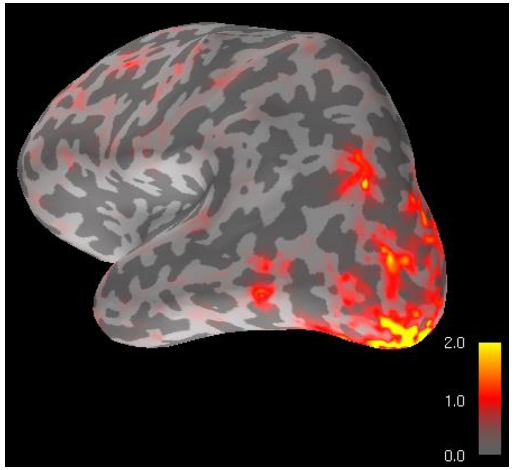
Magnetometers



Gradiometers

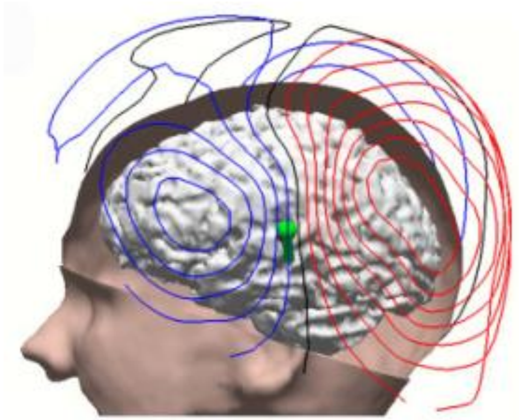


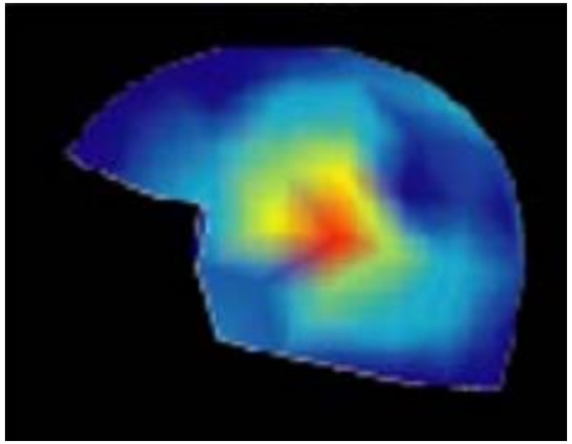
EEG

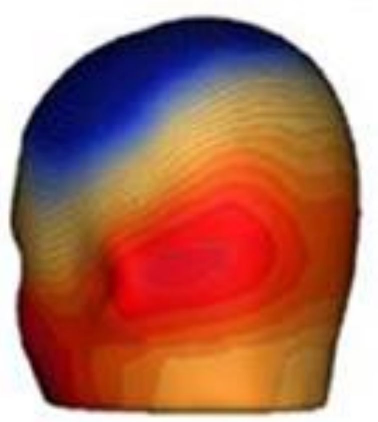


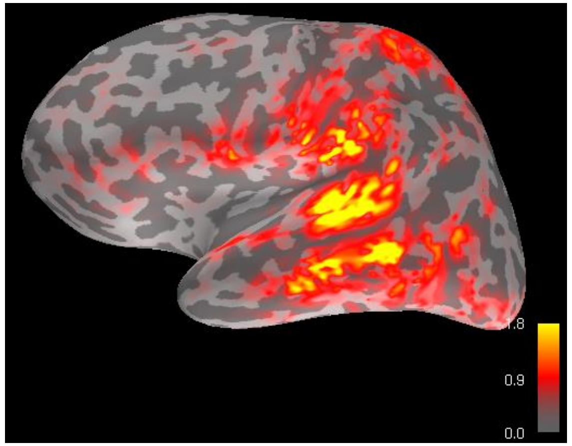
Minimum Norm Estimate

Example: Auditorily Evoked Activity









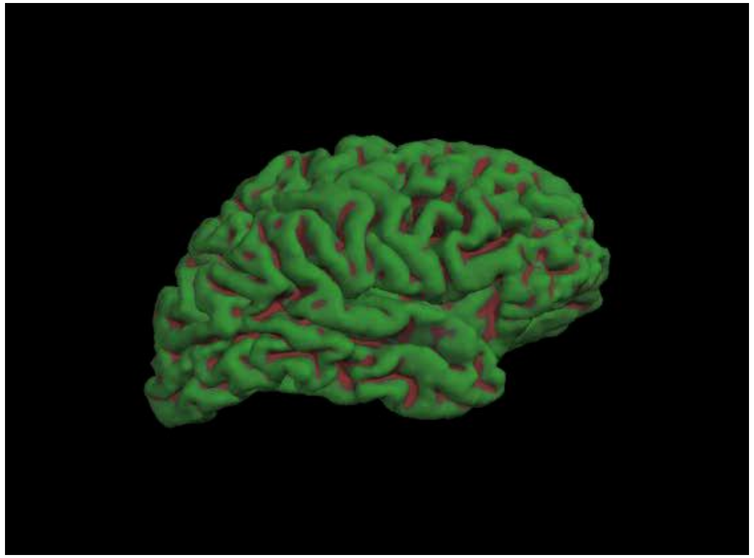
Minimum Norm Estimate

The Forward Problem and Head Modelling

Source Space and Head Model

Source Space

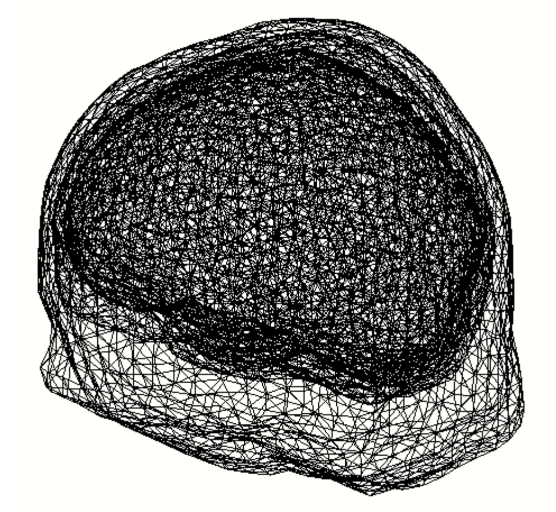
Where active sources may be located,
e.g. grey matter, 3D volume



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

Volume Conductor/Head Model

How we model conductivities/currents/potentials/fields in the head
e.g. sphere or realistic 1- or 3-compartments from MRI

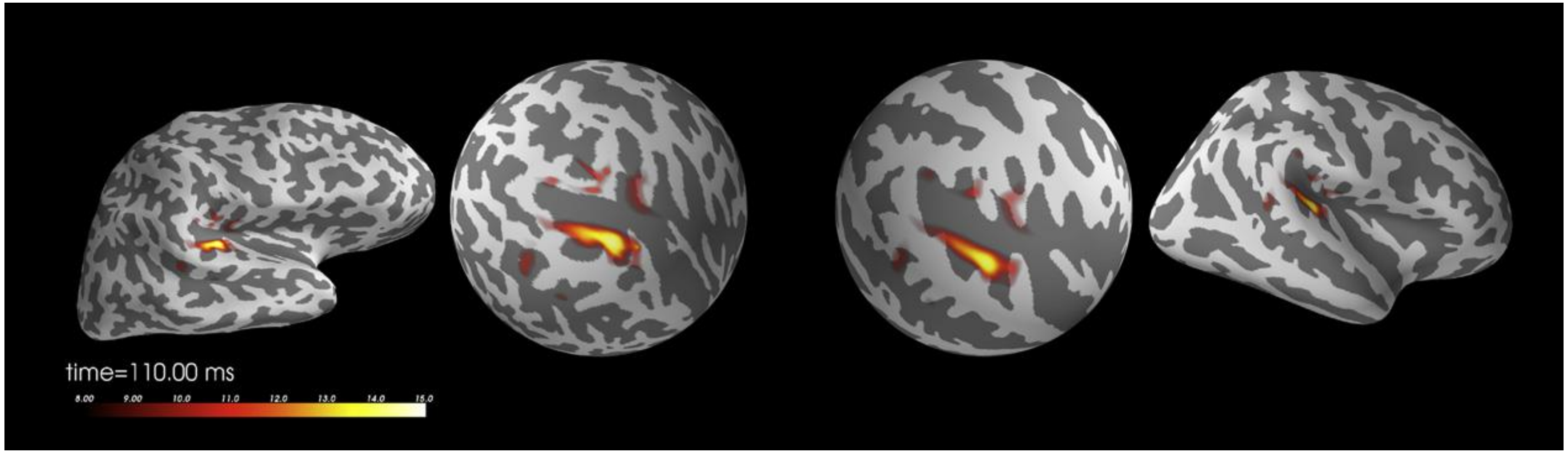


Sometimes “standard head models” are used, when no individual MRIs available.

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

Normalising (Morphing) Cortical Surfaces

From individual to standard brain

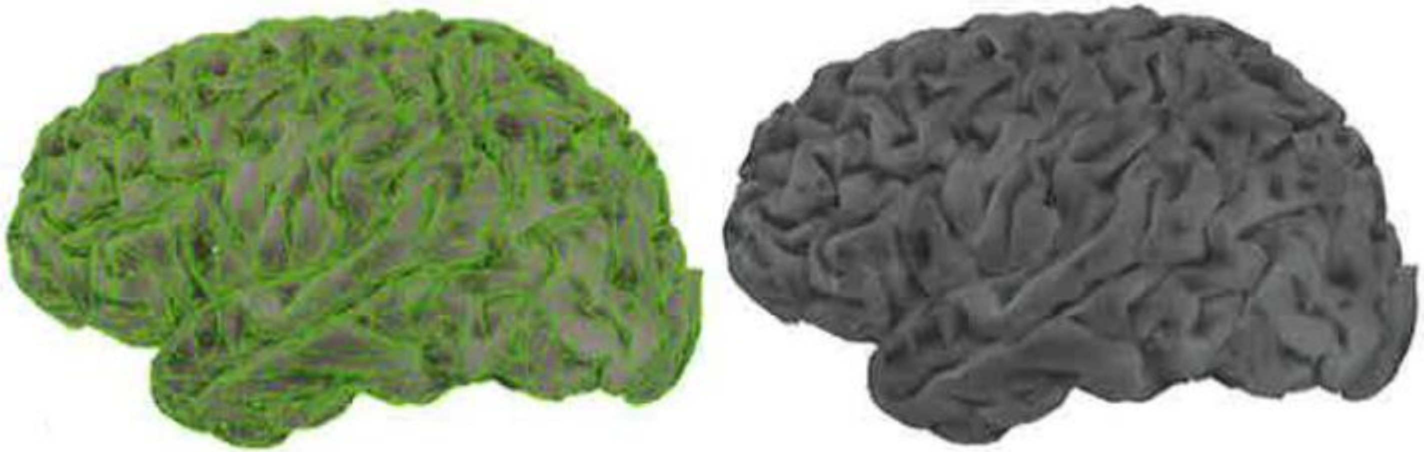


Gramfort et al., NI 2014

Spatial Sampling of Cortical Surfaces

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

Sufficient for most EEG/MEG applications

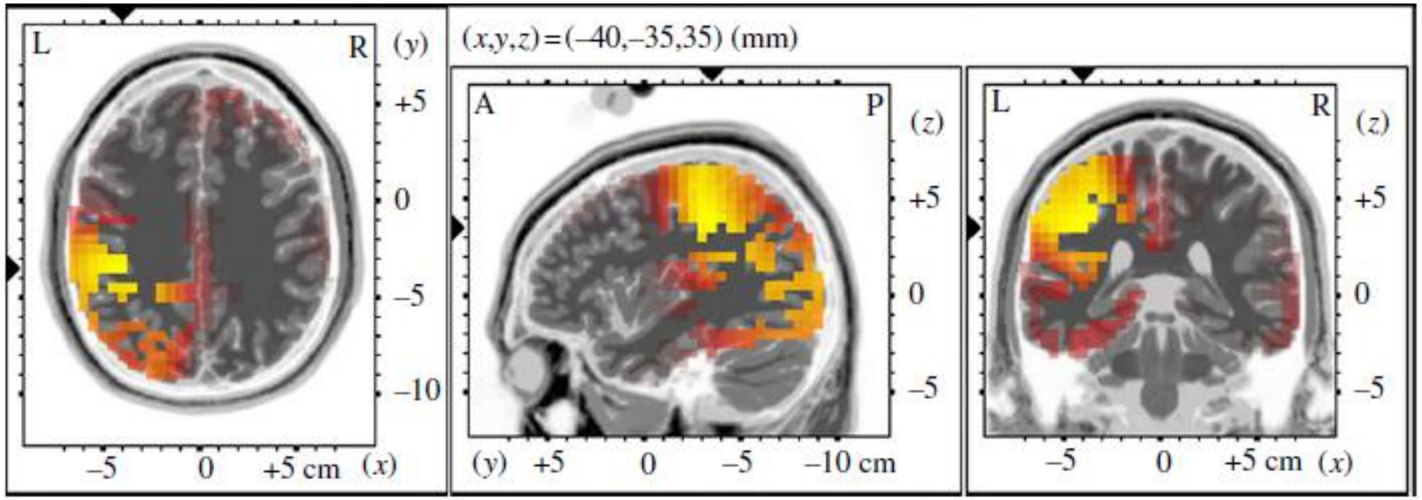


79.124 vertices, 158.456 triangles of 1.3 mm^2 surface area

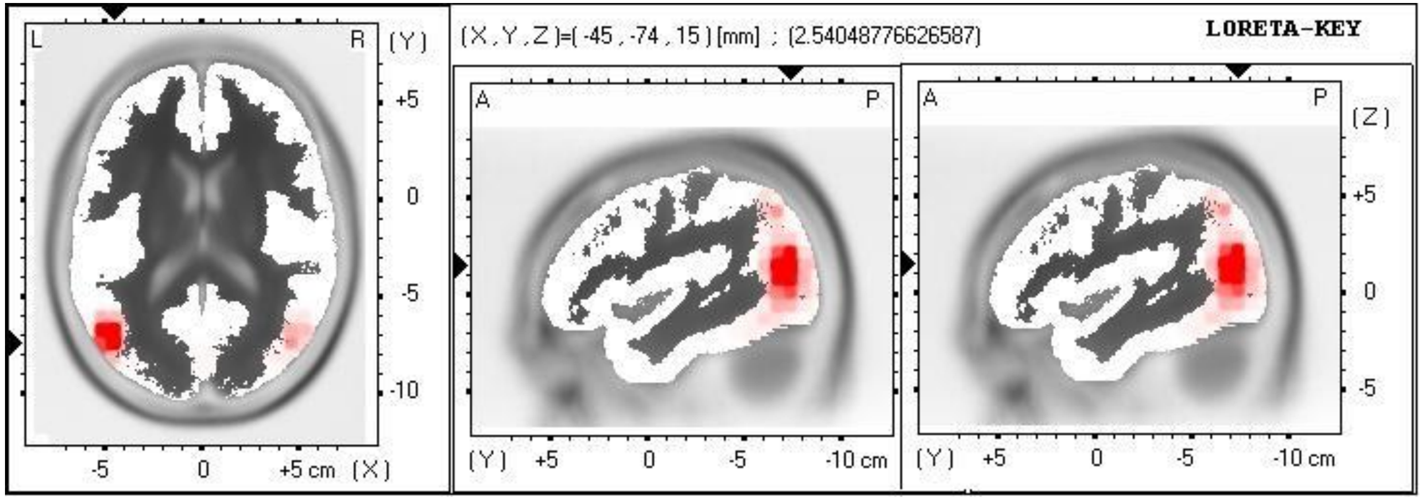
Baillet, chap. 5 in “MEG”, OUP 2010, Hansen/Kringelbach/Salmelin (edts.)

Volumetric Source Spaces Are Possible

But not necessarily useful considering the inverse problem is already highly underdetermined

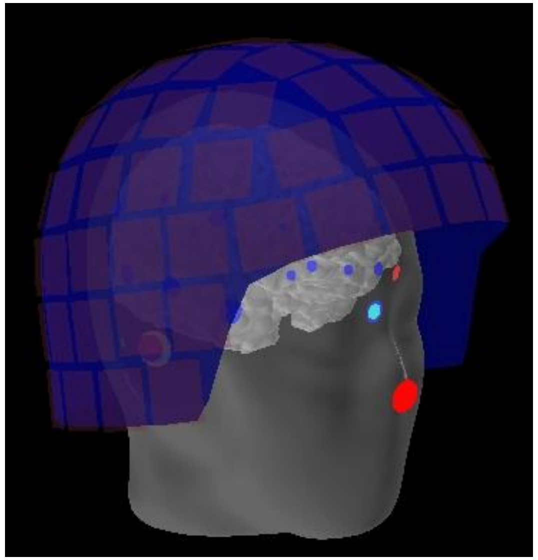


Pascqual-Marqui, PTRS-A 2011

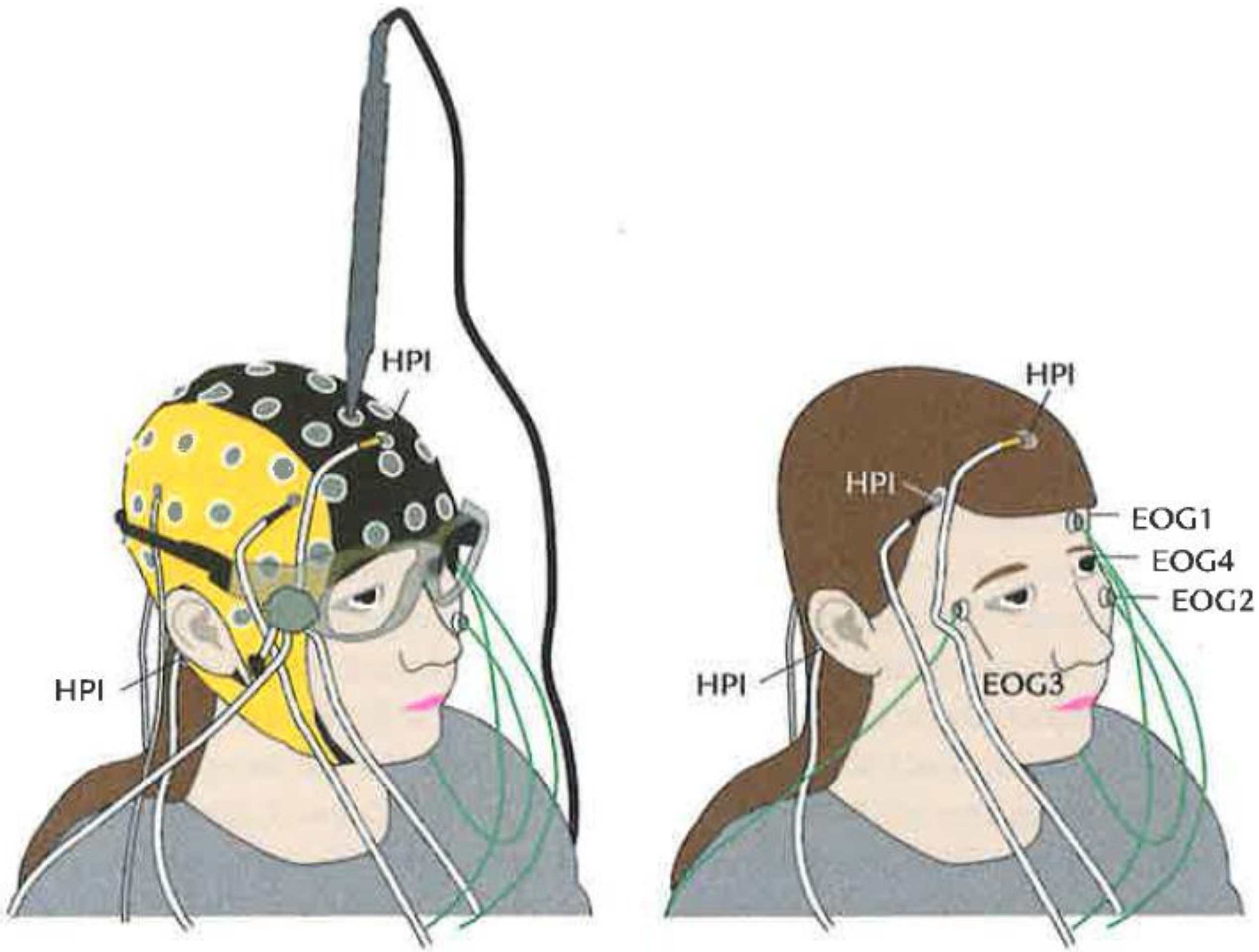


Coregistration of EEG/MEG and MRI Spaces

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

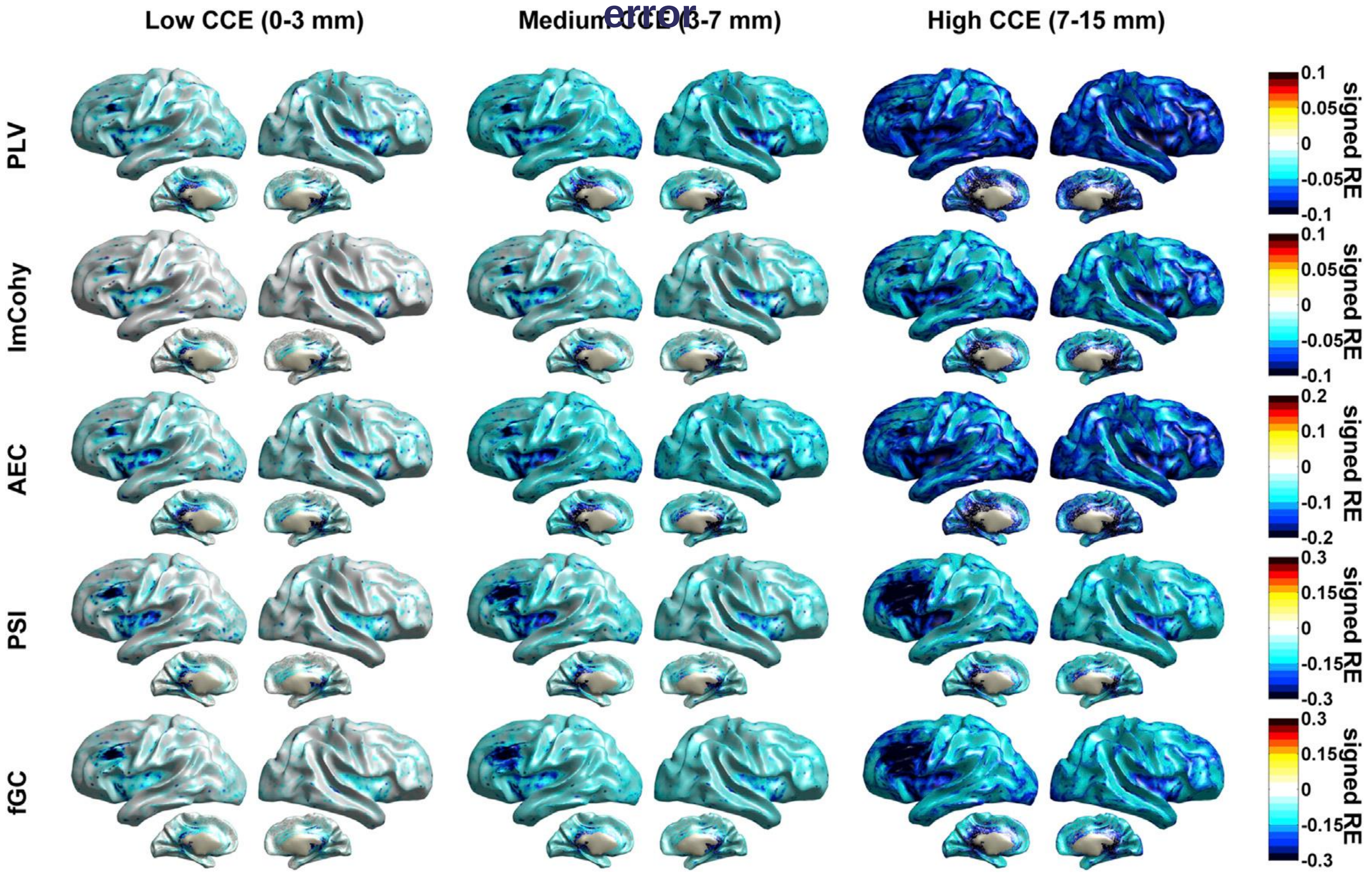
Accurate Coregistration Is Important

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

For example, connectivity analysis:

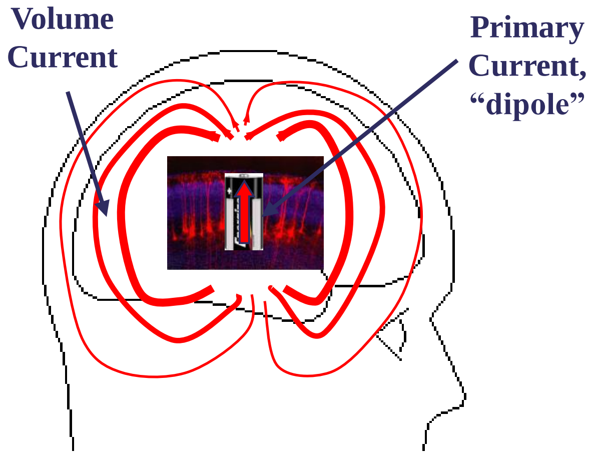
3 levels of coregistration error

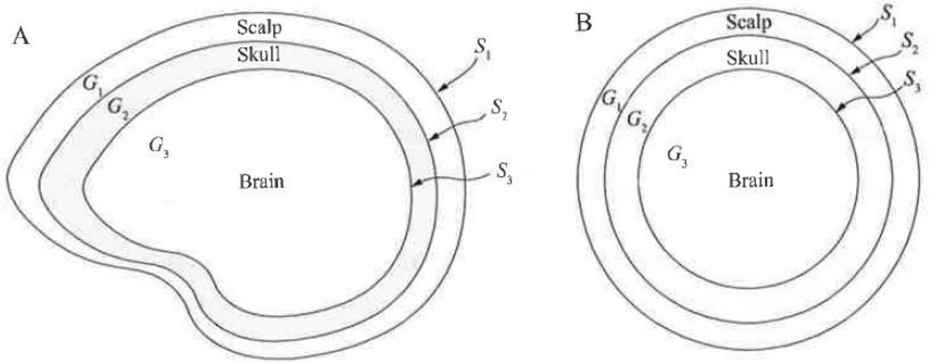
Functional Connectivity Metrics



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

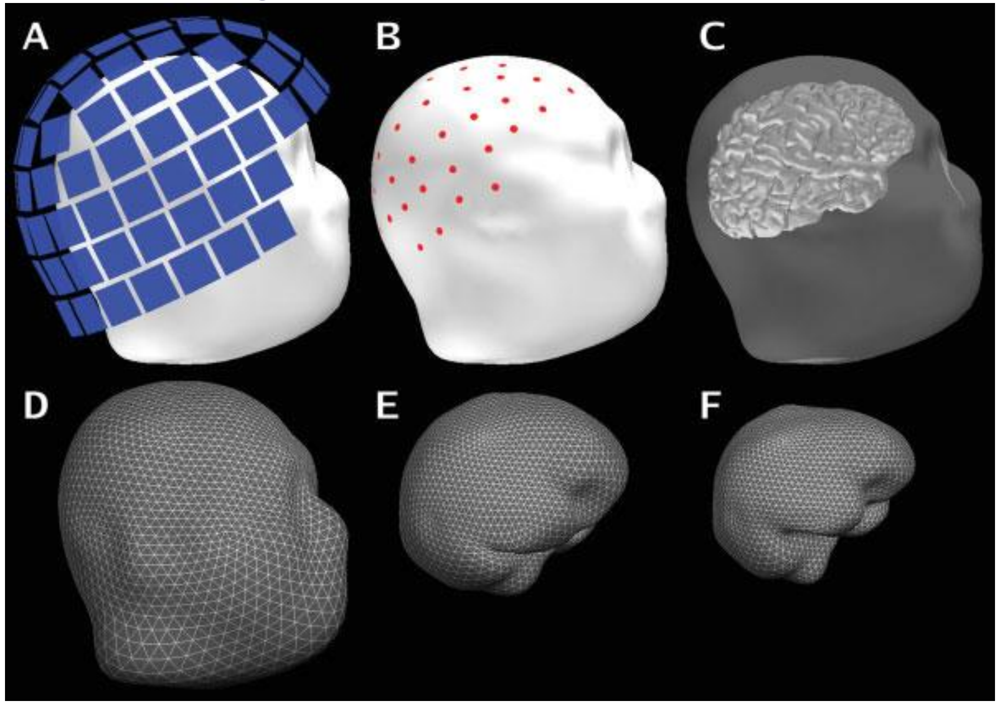
Boundary Element Model (BEM)





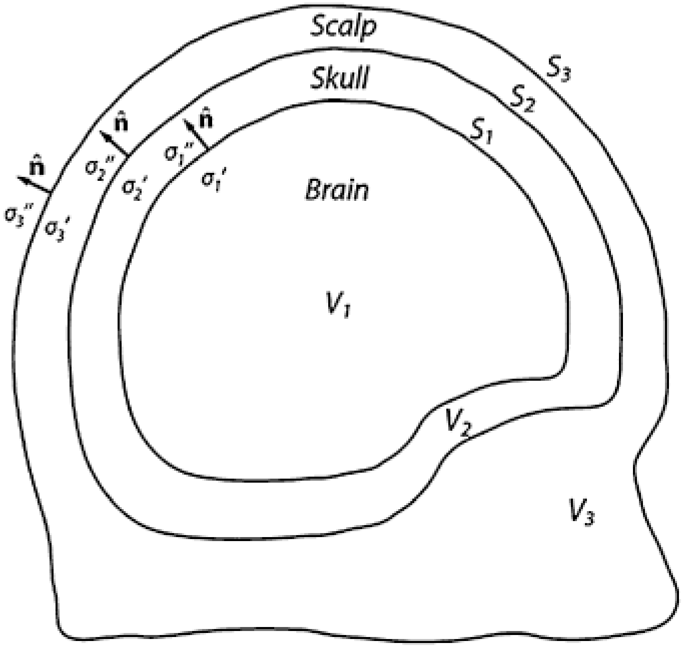
Ilmoniemi and Sarvas, “Brain Signals”, MIT 2019

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

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

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

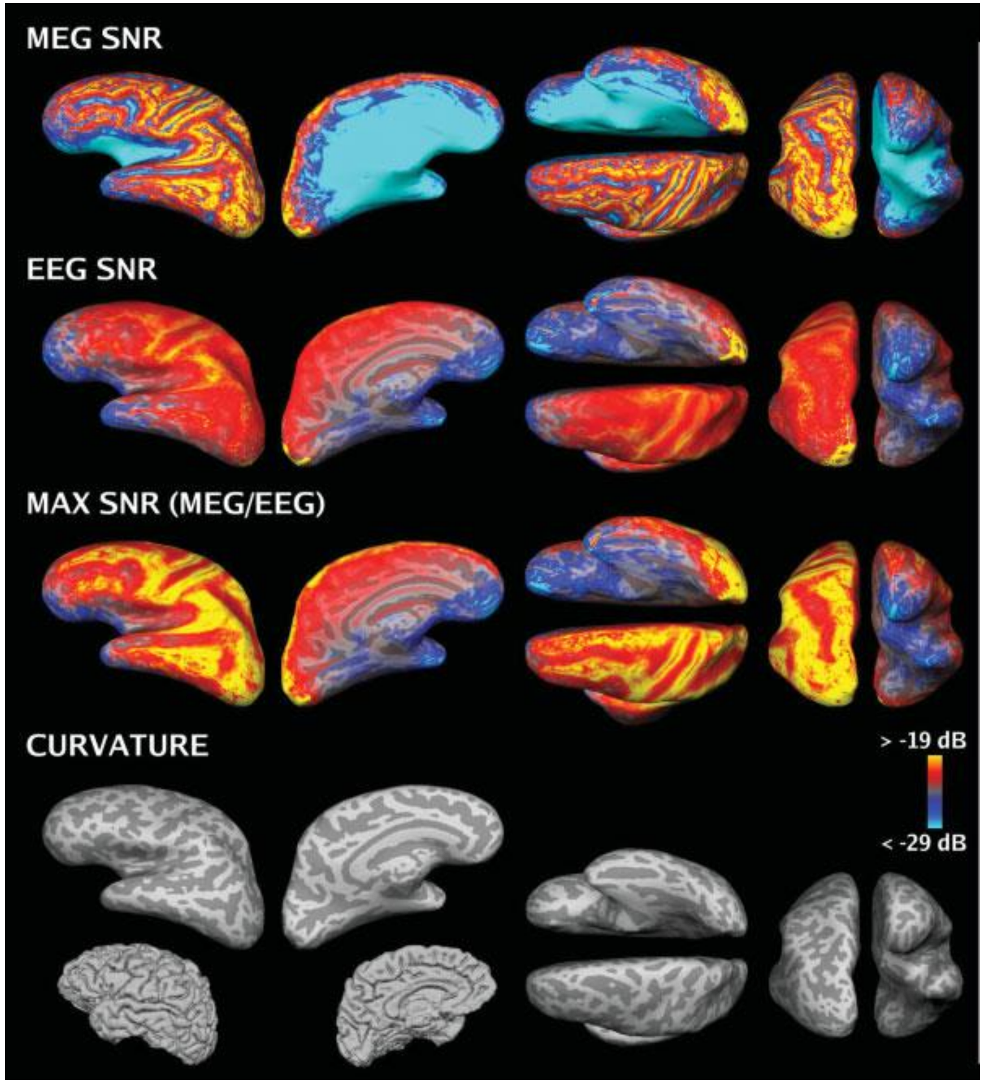
Heller & Volegov, in Magnetoencephalography by Supek & Aine (edts), Springer 2019

- Volume currents depend on conductivity distribution within the whole head volume.
- EEG measurements on the scalp depend on 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.

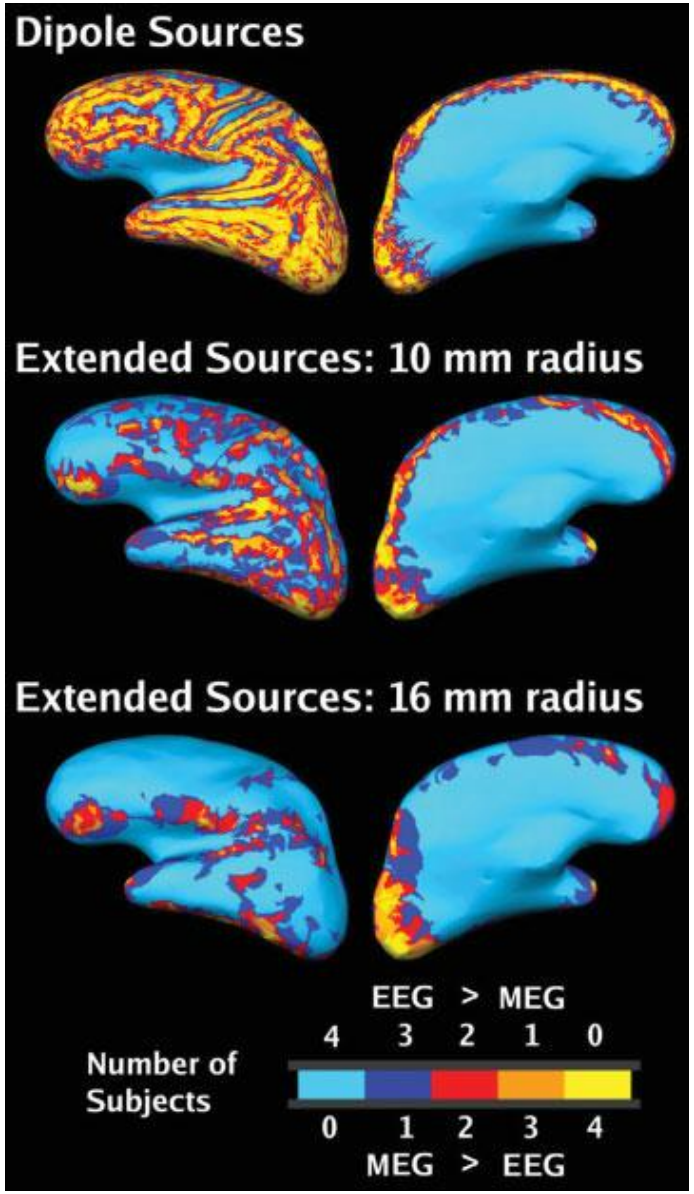
Sensitivity Maps

Sensor type, coverage and distance to sources strongly affects 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



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

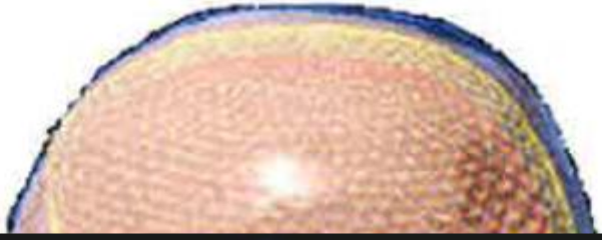
Fixing Head Models

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

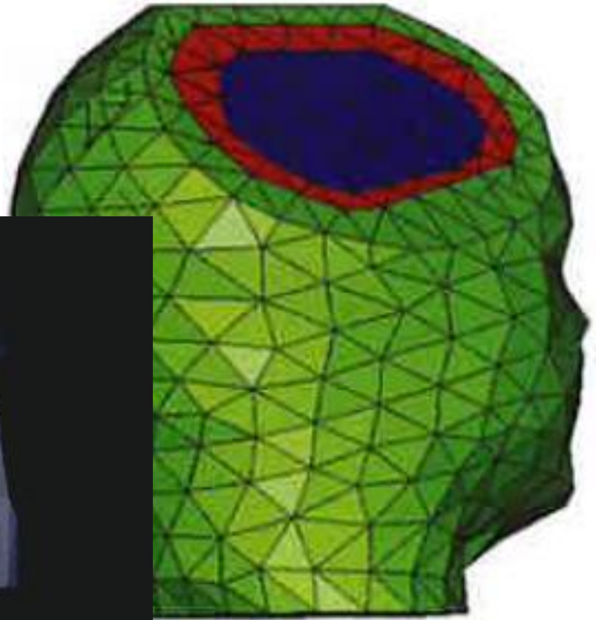
Head Models With Different Levels of Detail

Spheres

Boundary Element Model (BEM)



Finite Element Model (FEM)



Kraftwerk, 1986

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

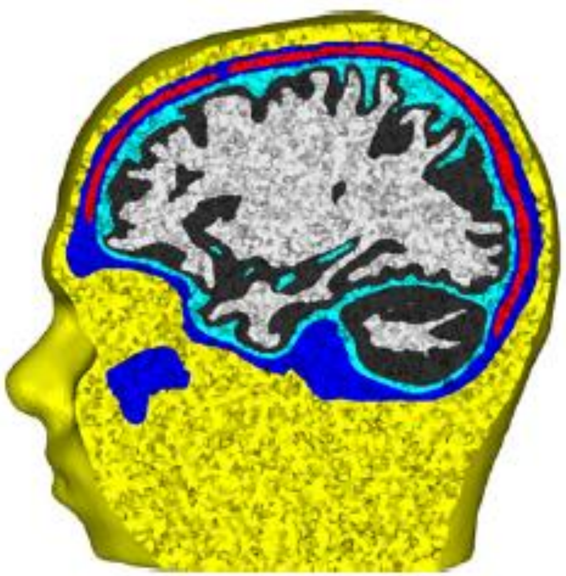
More Complex Head Models

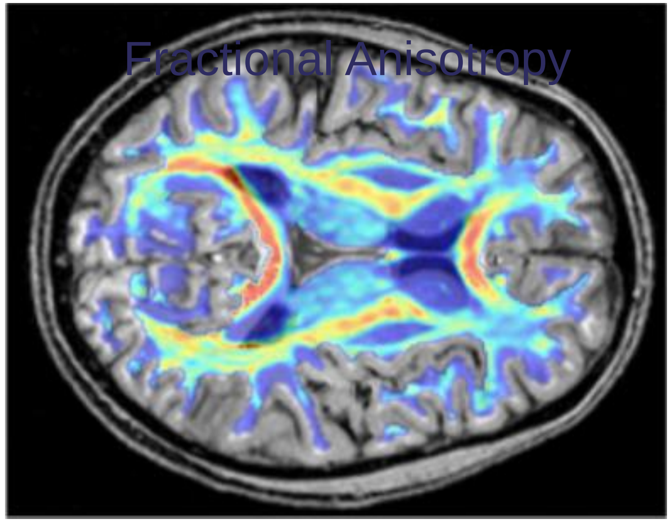
The use of 3-layer (brain, skull, scalp) BEM models based on individual MRI images is recommended for accurate EEG/MEG source reconstruction.

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





Vorwerk et al., NI 2014

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

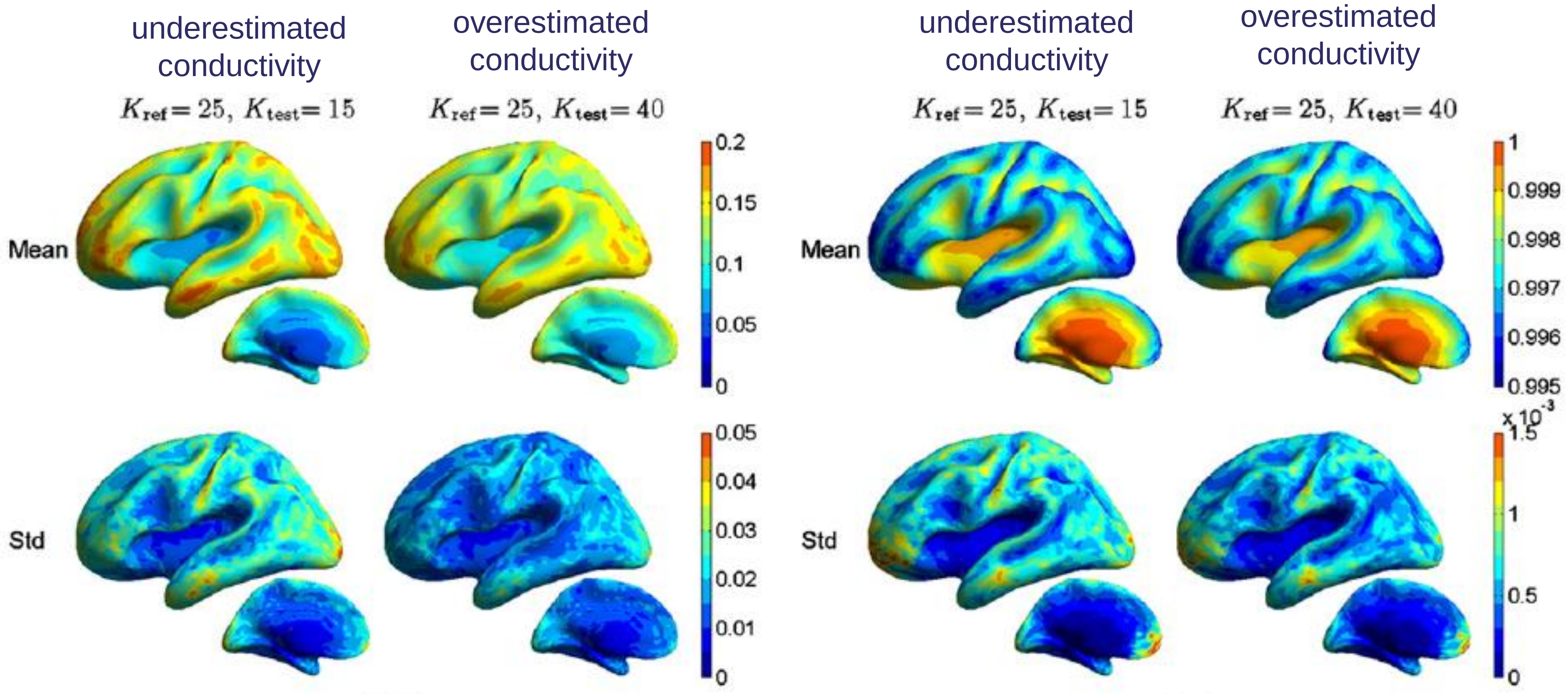
Conductivities Of Tissues Can Only Be Approximated

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.)

Boundary Element Models Are Relatively Robust Against Conductivity Errors

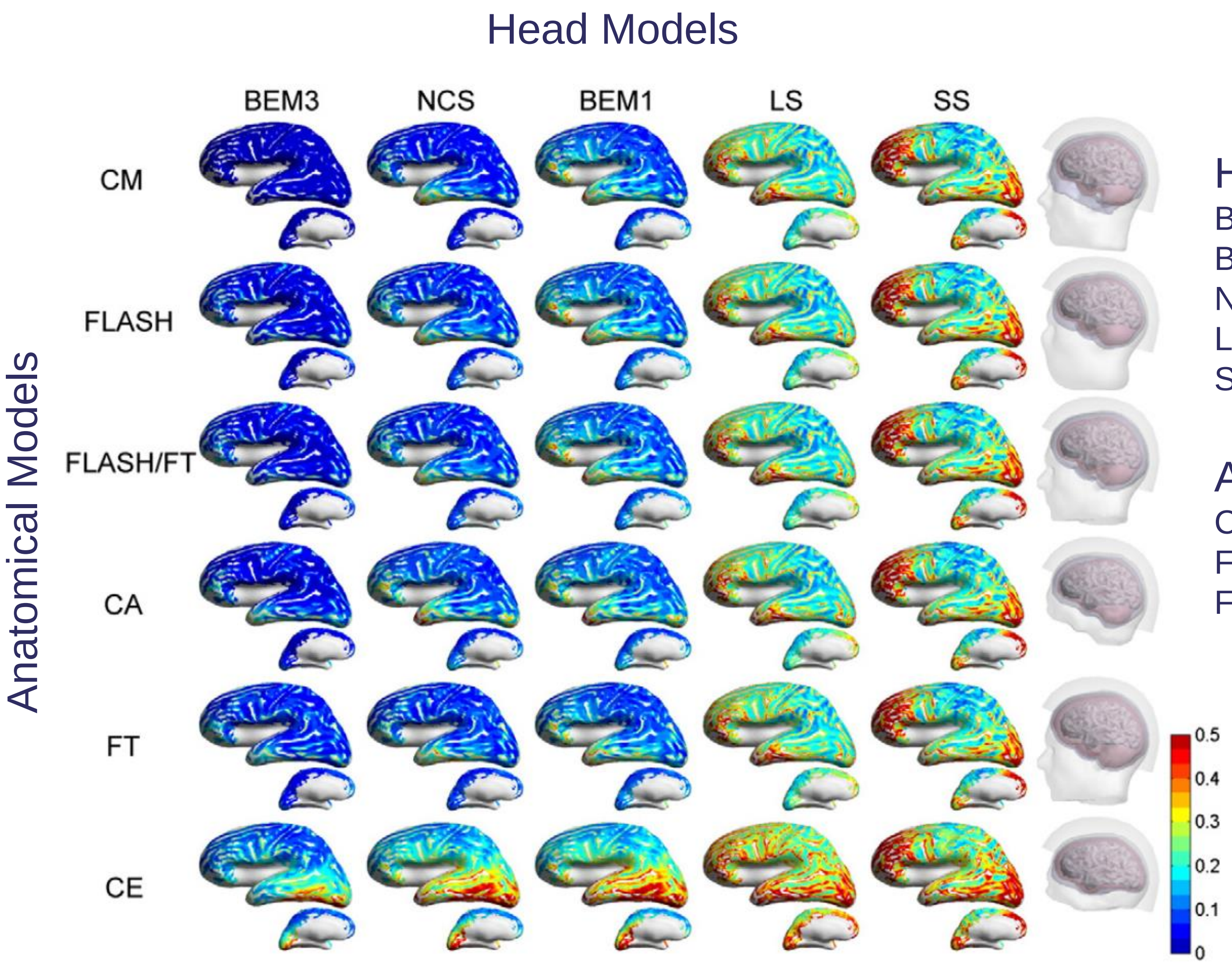


Relative Error

Correlation Coefficient

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

The Effect of Head Model Accuracy for MEG



Relative Error

Head Models:

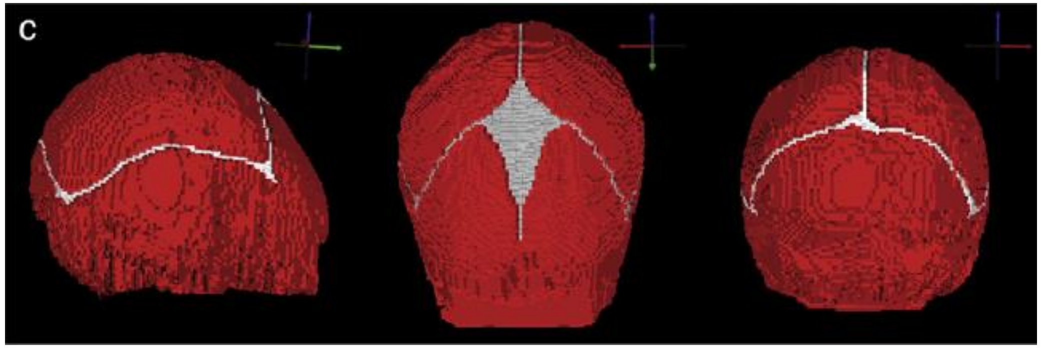
BEM3: BEM 3-shell
BEM1: 1-shell
NCS: Nolte Corrected Sphere
LS: Local Sphere
SS: Single Sphere

Anatomical Models:

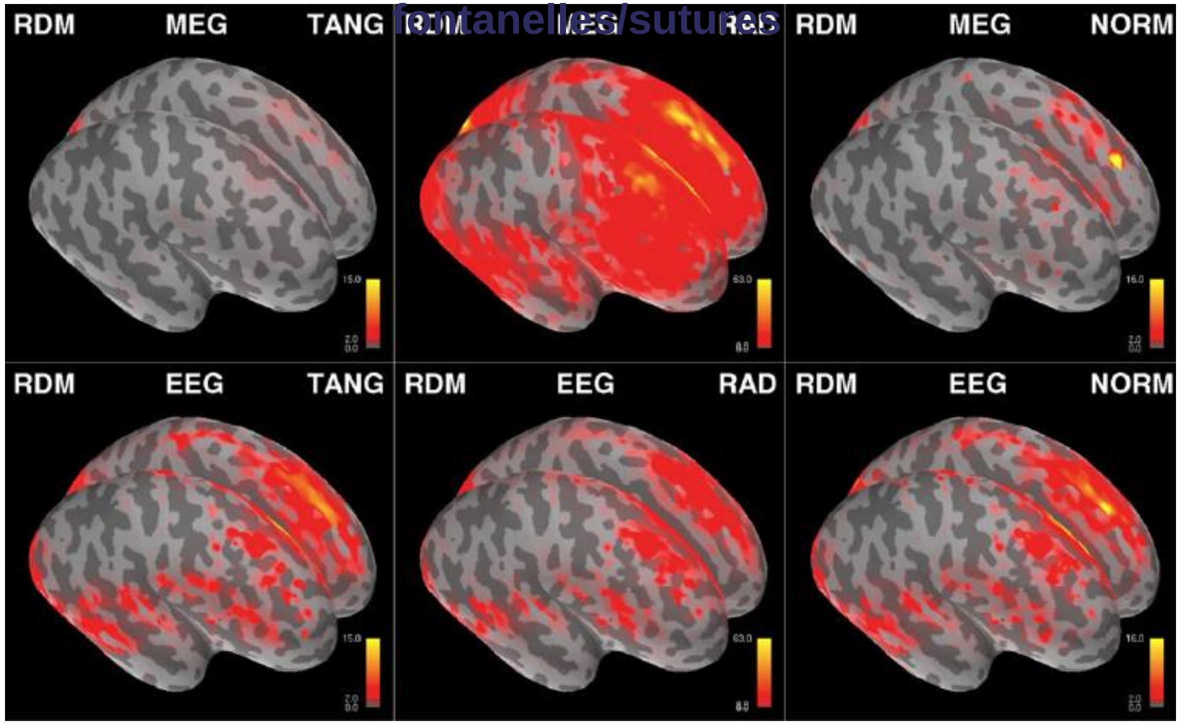
CA/CE: Curry
FLASH: Freesurfer
FT: Fieldtrip

Stenroos, Neuroimage 2014

Infant Skulls – Fontanelles and Sutures



Relative error between models with and without fontanelles/sutures



Lew et al., NI 2013

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.

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Thank you