



MRC Cognition
and Brain
Sciences Unit



UNIVERSITY OF
CAMBRIDGE

EEG/MEG 2: Head and Forward Modelling

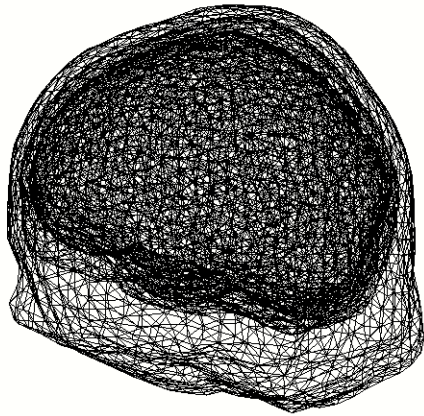
Olaf Hauk

olaf.hauk@mrc-cbu.cam.ac.uk

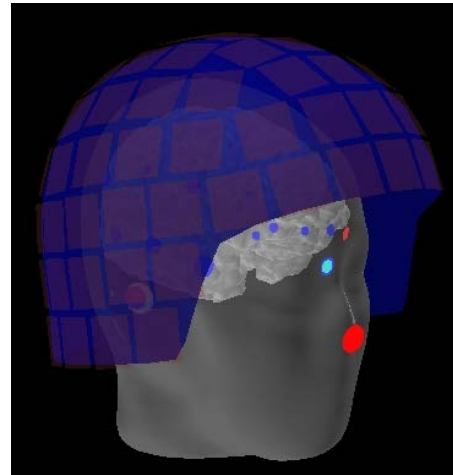
COGNESTIC 2022

Ingredients for Source Estimation

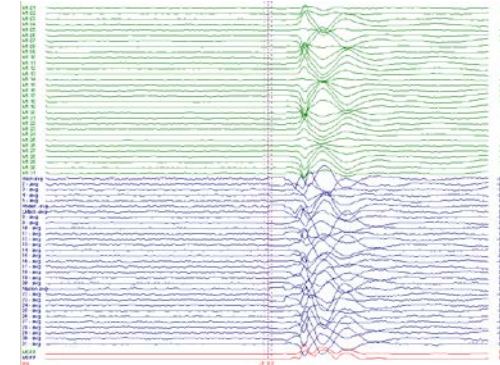
Volume Conductor/
Head Model



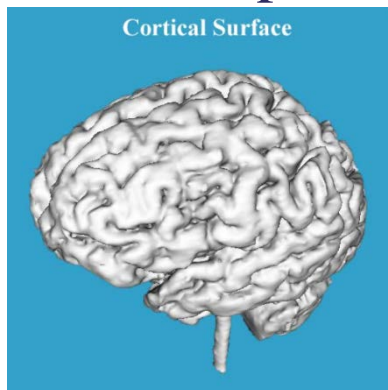
Coordinate
Transformation



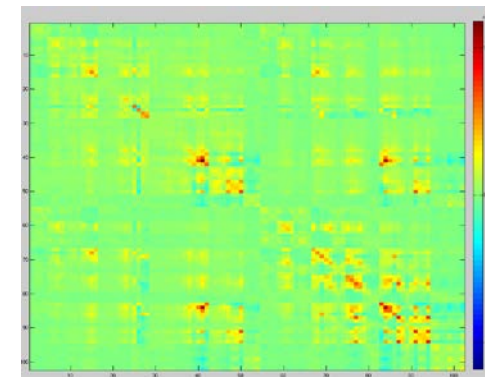
MEG data



Source Space

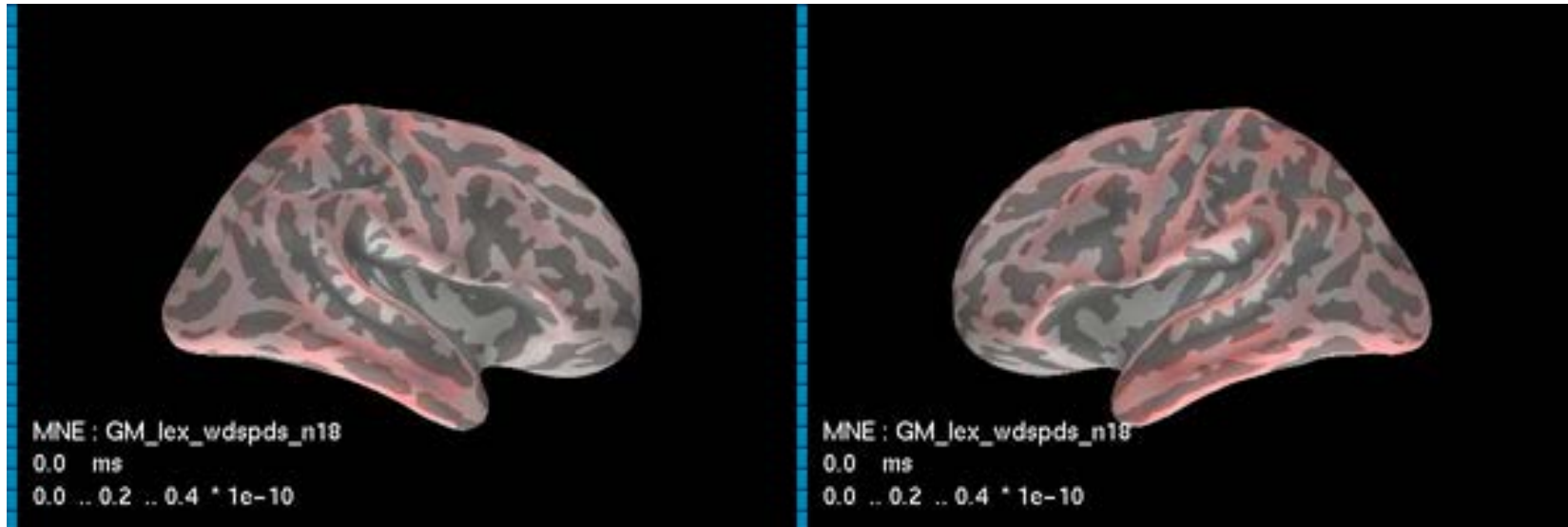


Noise/Covariance Matrix



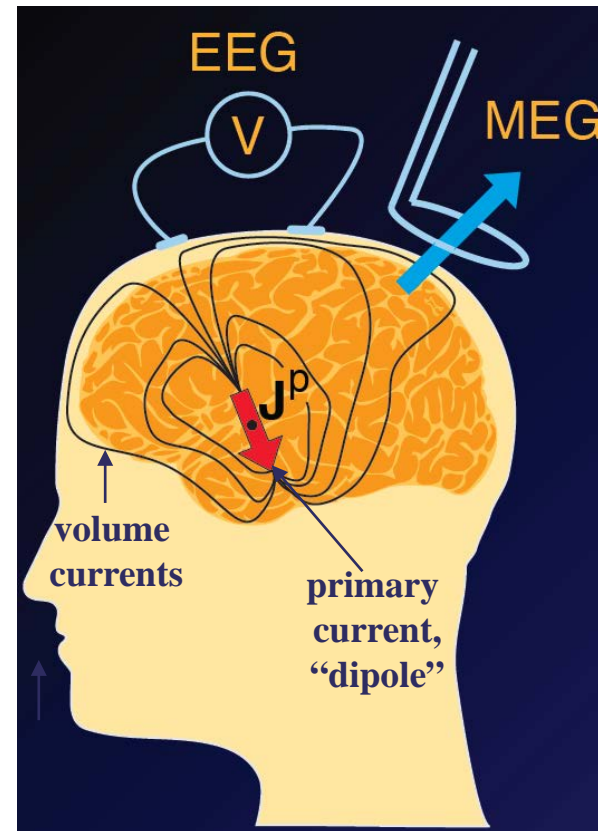
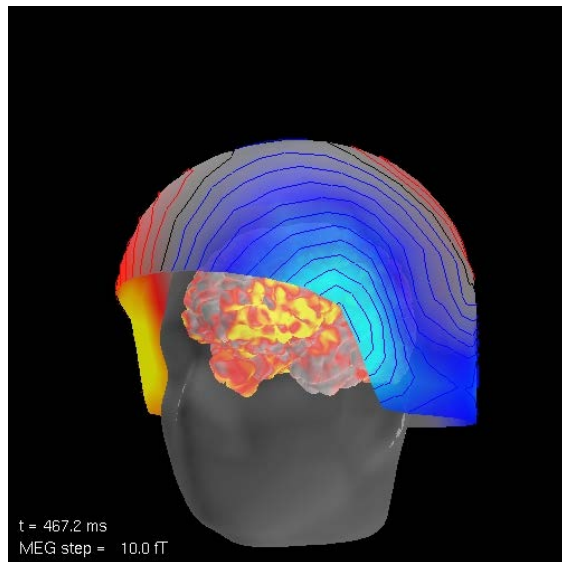
Our Goal: Spatio-Temporal Brain Dynamics

“Brain Movies”

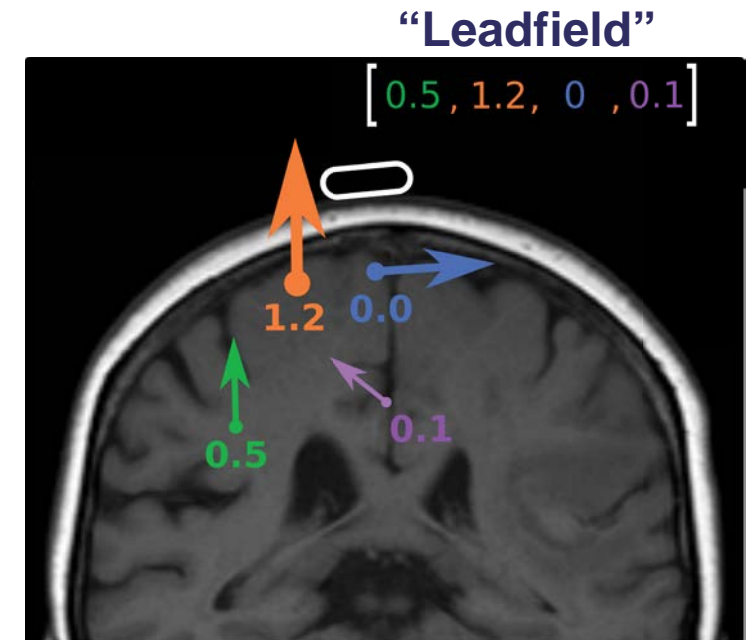


The EEG/MEG Forward Problem

EEG/MEG measure the primary sources indirectly

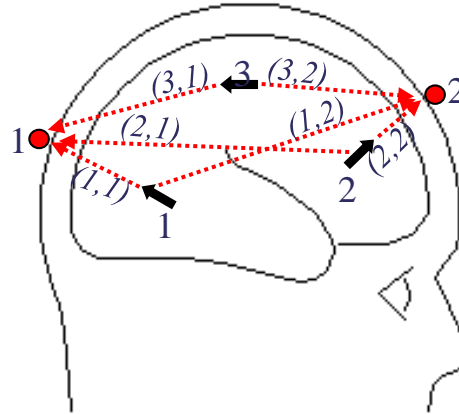


Sensors are differently sensitive to different sources



Hauk, Stenroos, Tredner. In: Supek S, Aine C (eds), "Magnetoencephalography: From Signals to Dynamic Cortical Networks, 2nd Ed."

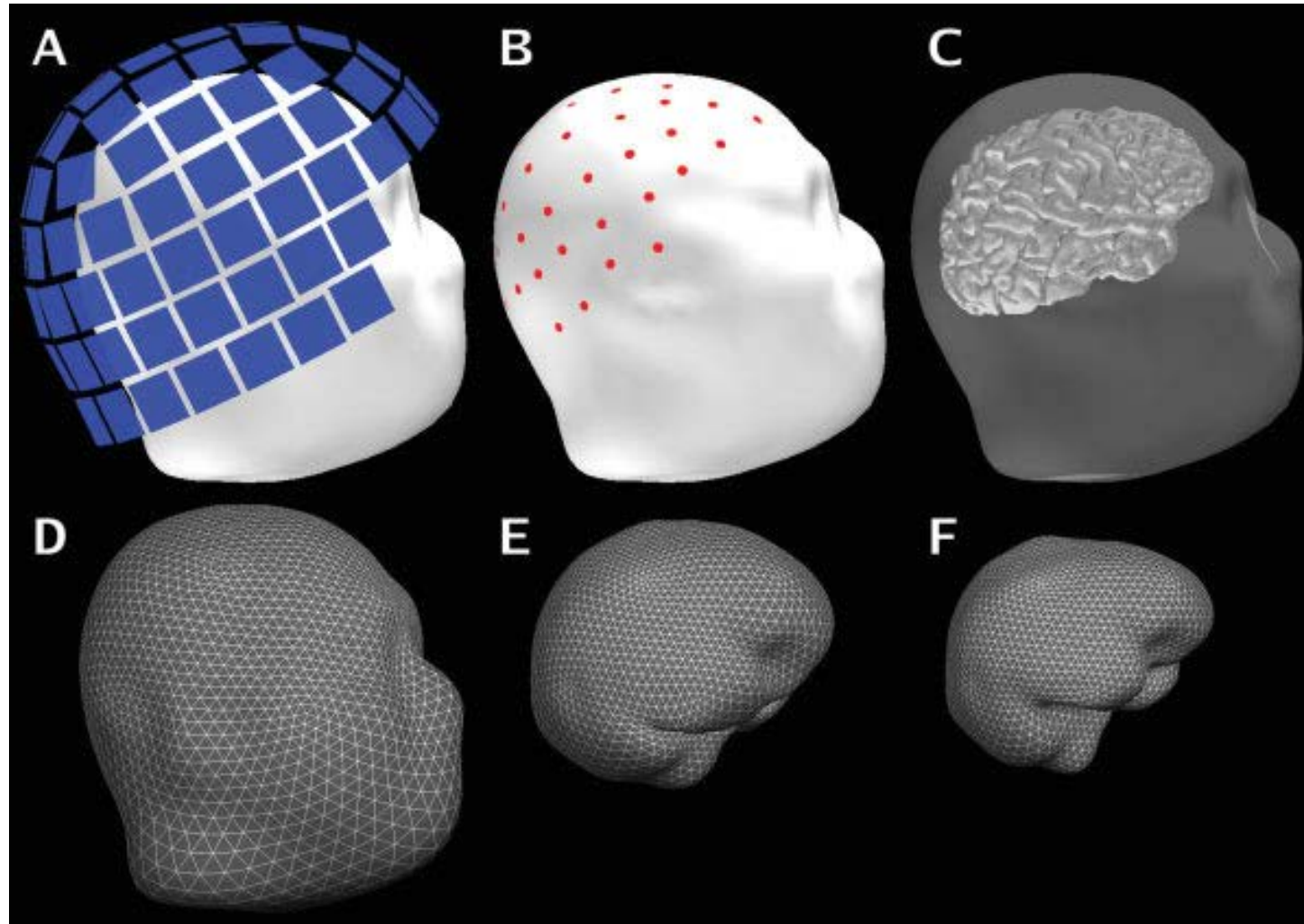
We Have To First State The Forward Problem In Order To Solve The Inverse Problem



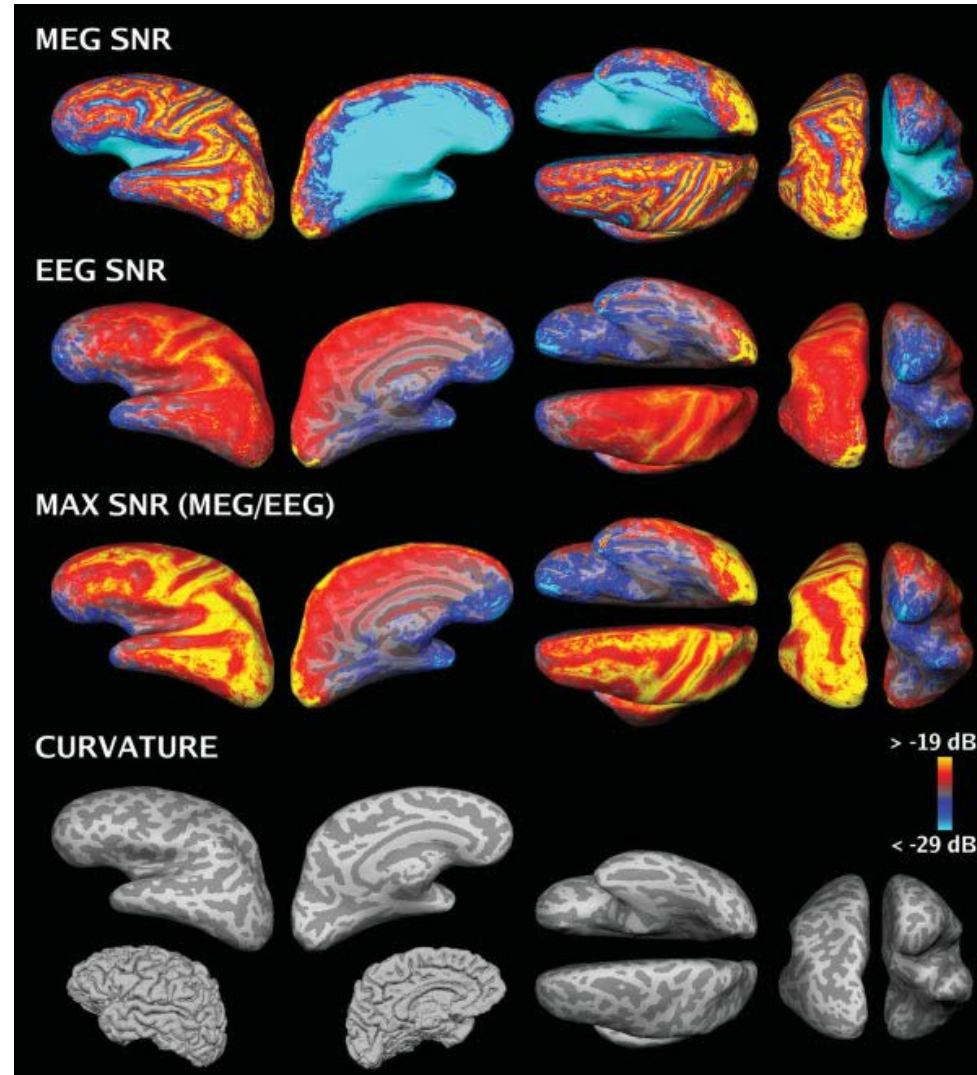
Inverse Operator

data	“leadfield”	dipoles	?	dipoles	inverse	data
$\begin{matrix} 1 \\ \bullet \end{matrix} \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$	$= \begin{pmatrix} 0.5 & 0 & 0.3 \\ 0 & 1 & -0.3 \end{pmatrix}$	$\begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix}$	$\xrightarrow{\text{inversion}}$	$\begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix}$	$= \begin{pmatrix} 1.5034 & 0.1241 \\ 0.2483 & 0.9379 \\ 0.8276 & -0.2069 \end{pmatrix}$	$* \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}$

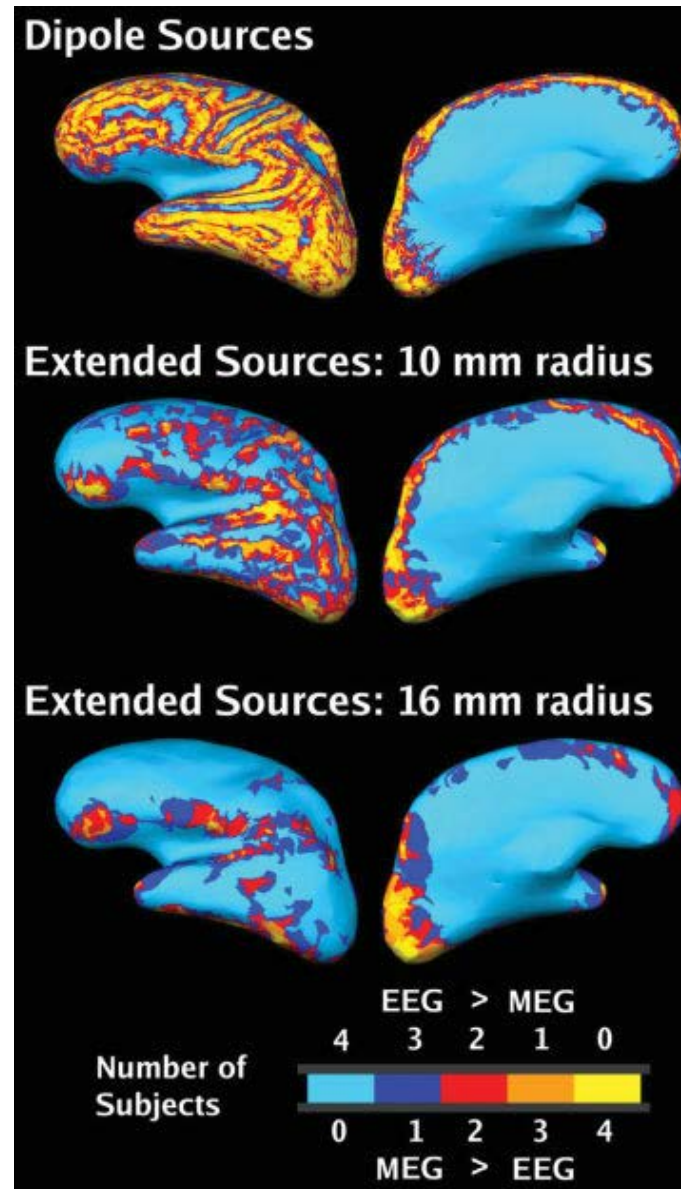
Ingredients for a head model



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

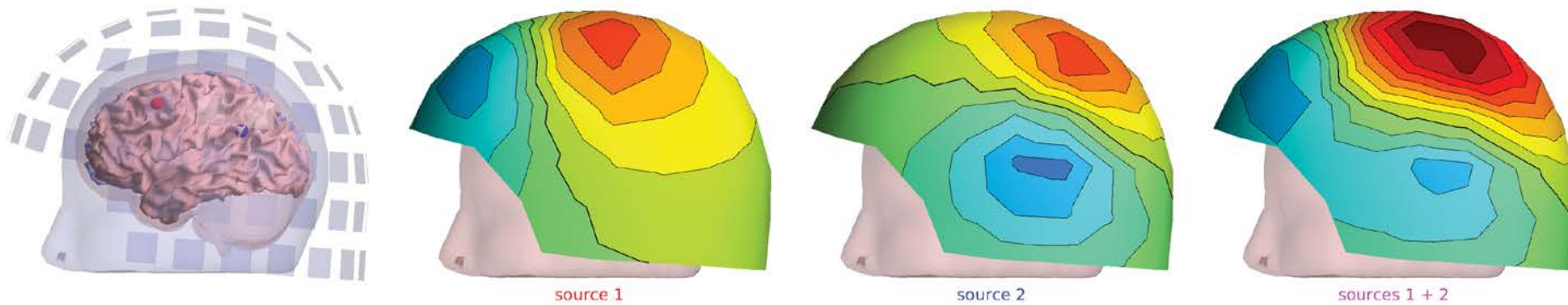


MEG Is Less Sensitive To Spatially Extended Sources Than EEG

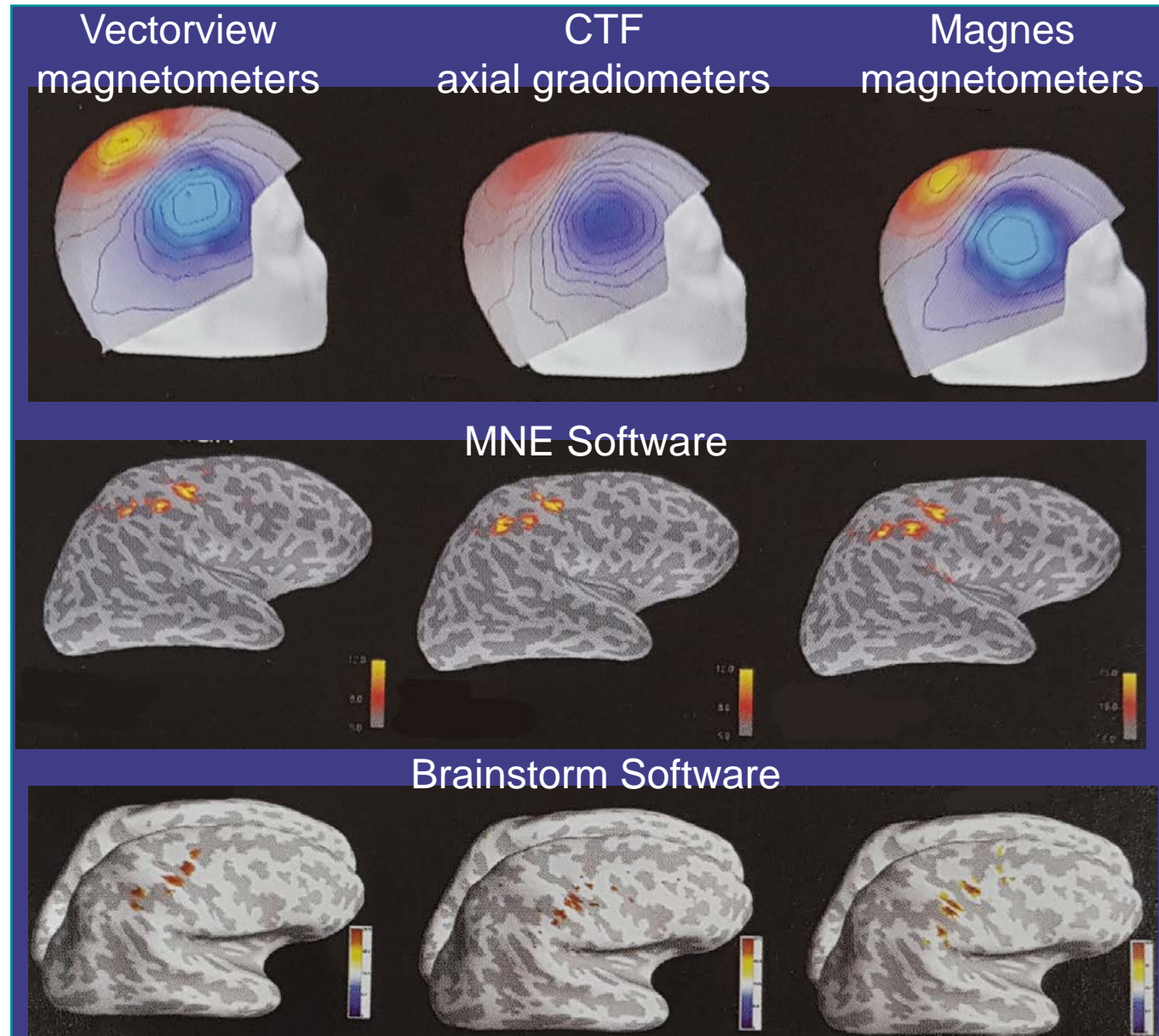


The Forward Problem Is Linear – Superposition Principle

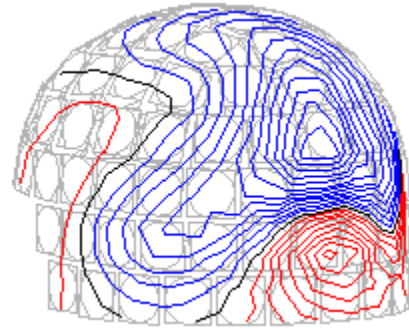
Superposition In Sensor Space



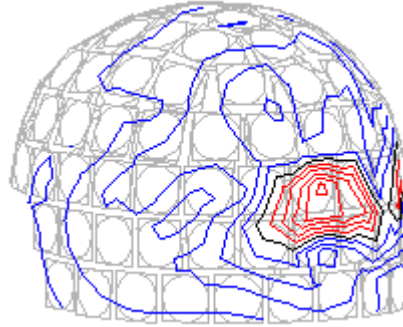
Different MEG Systems, Similar Magnetic Fields



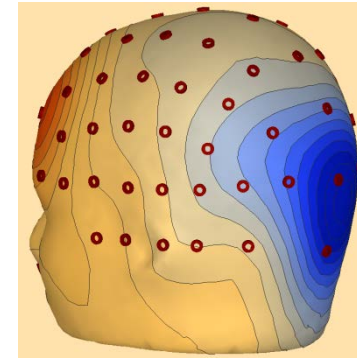
Example: Visually Evoked Activity ~100 ms



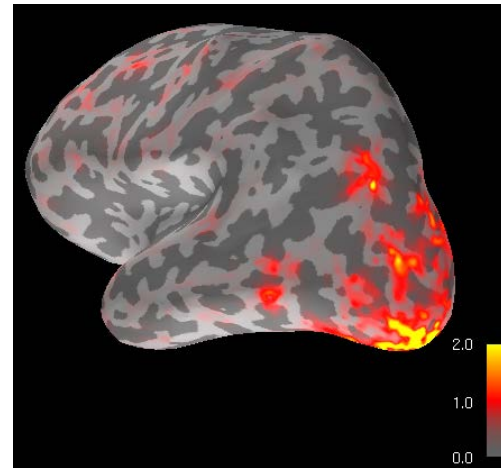
Magnetometers



Gradiometers

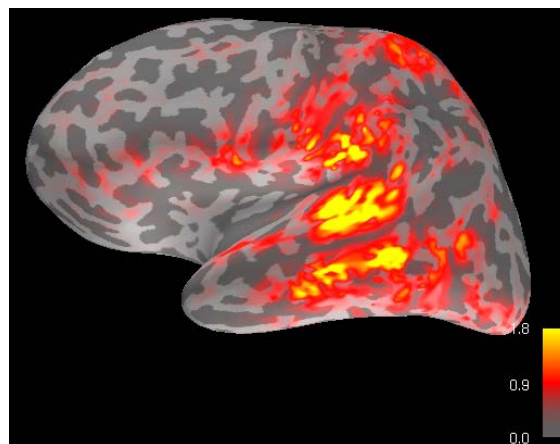
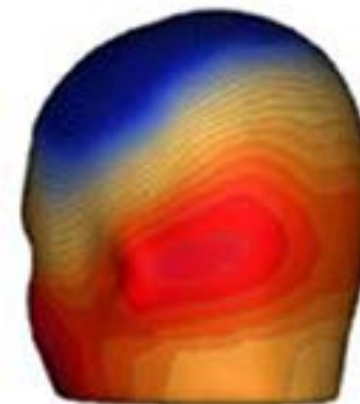
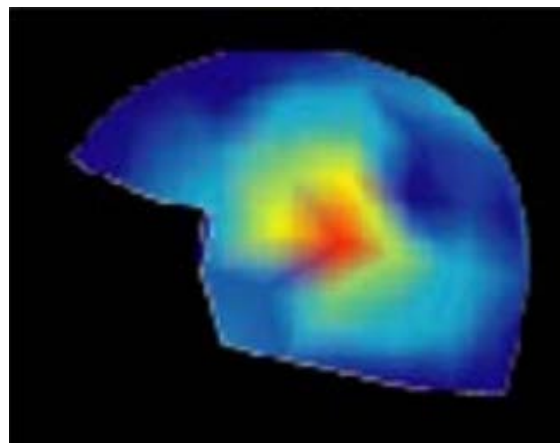
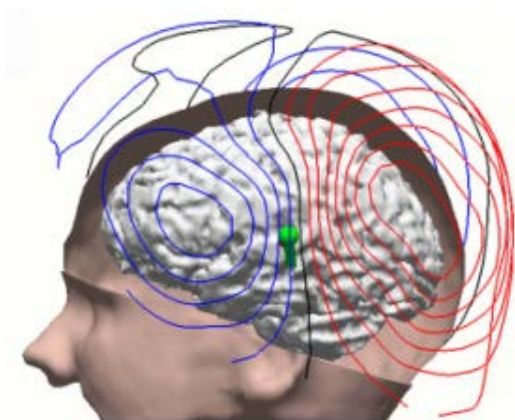


EEG



Minimum Norm Estimate

Example: Auditorily Evoked Activity



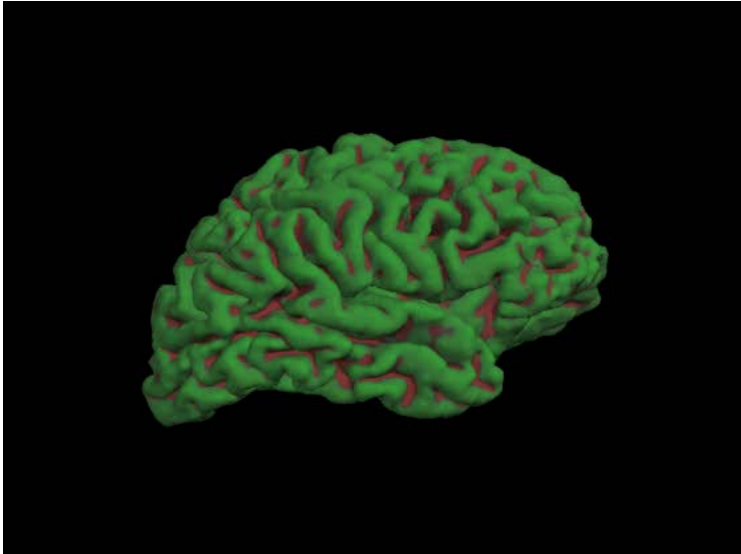
Minimum Norm Estimate

The Forward Problem and Head Modelling

Source Space and Head Model

Source Space

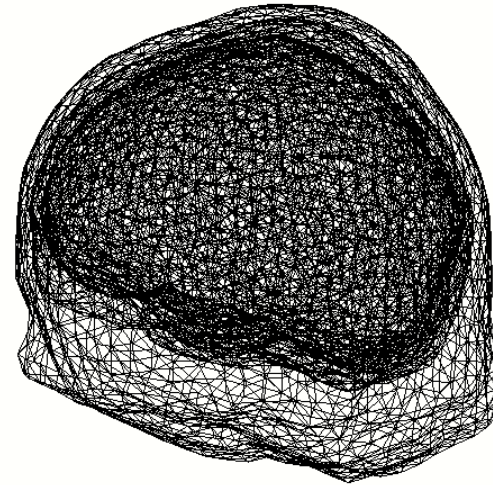
Where active sources may be located,
e.g. grey matter, 3D volume



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

Volume Conductor/Head Model

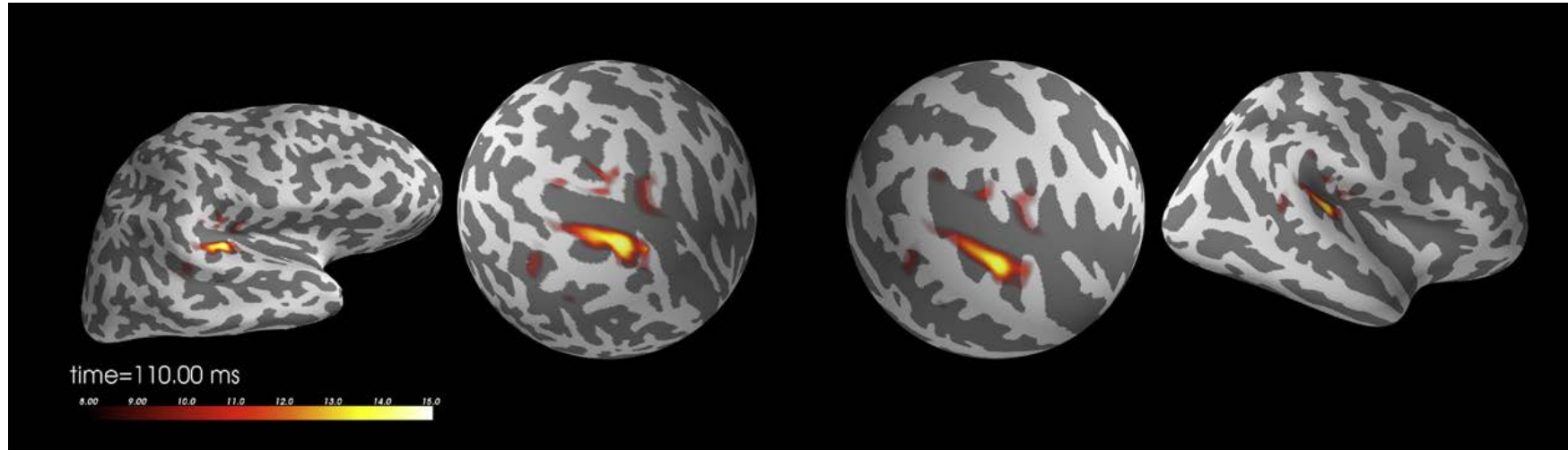
How we model conductivities/currents/potentials/fields in the head
e.g. sphere or realistic 1- or 3-compartment from MRI



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.

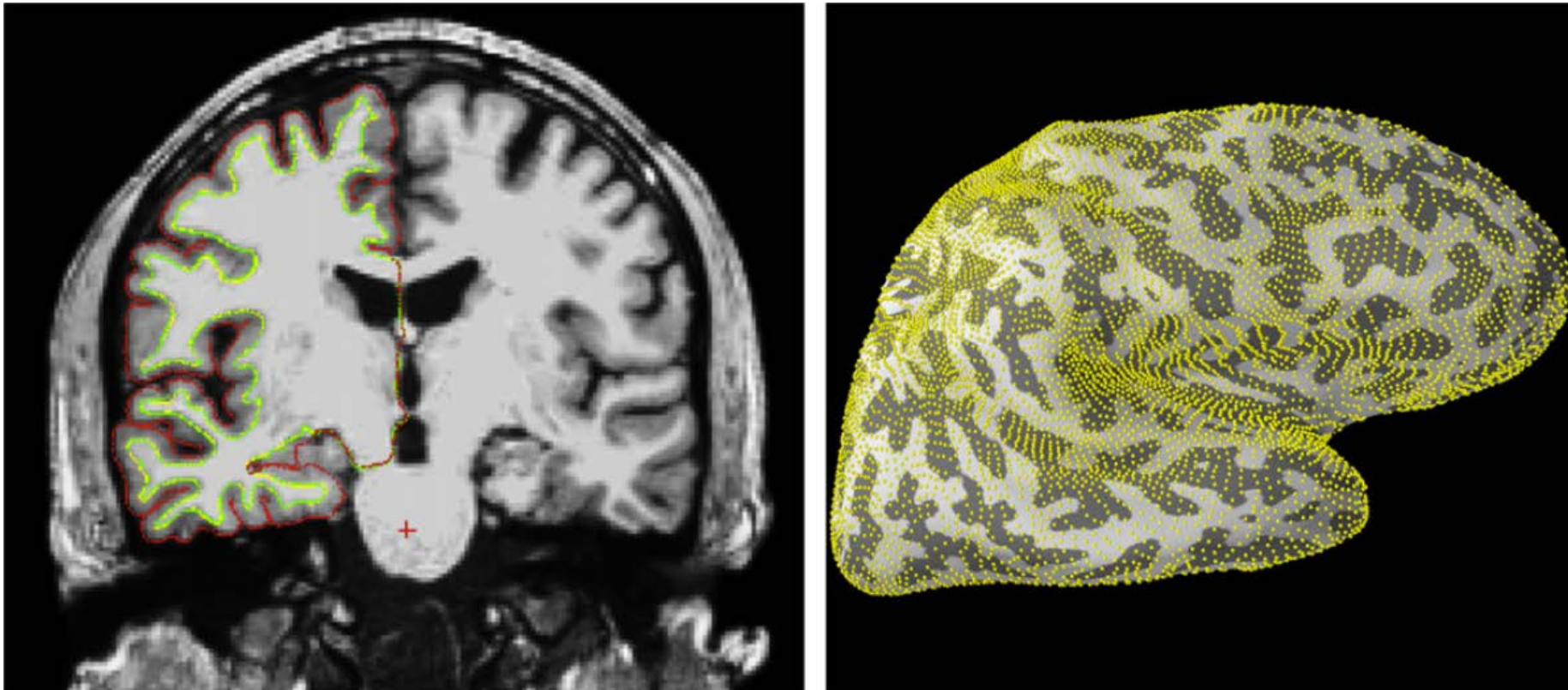
Normalising (Morphing) Cortical Surfaces

From individual to standard brain



Gramfort et al., NI 2014

Source Spaces: Cortical Surface Segmentation

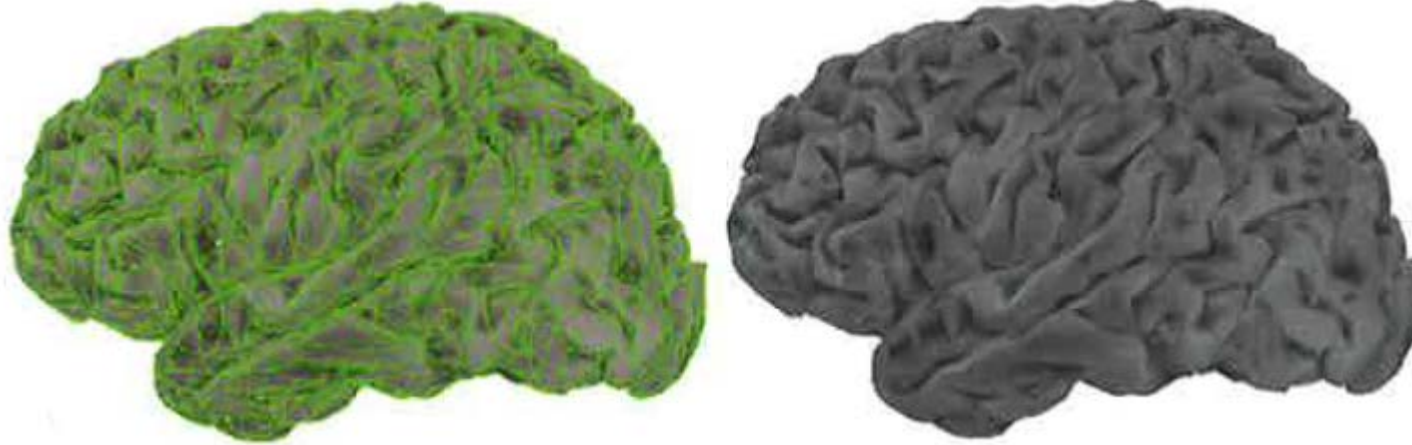


Gramfort et al., NI 2014

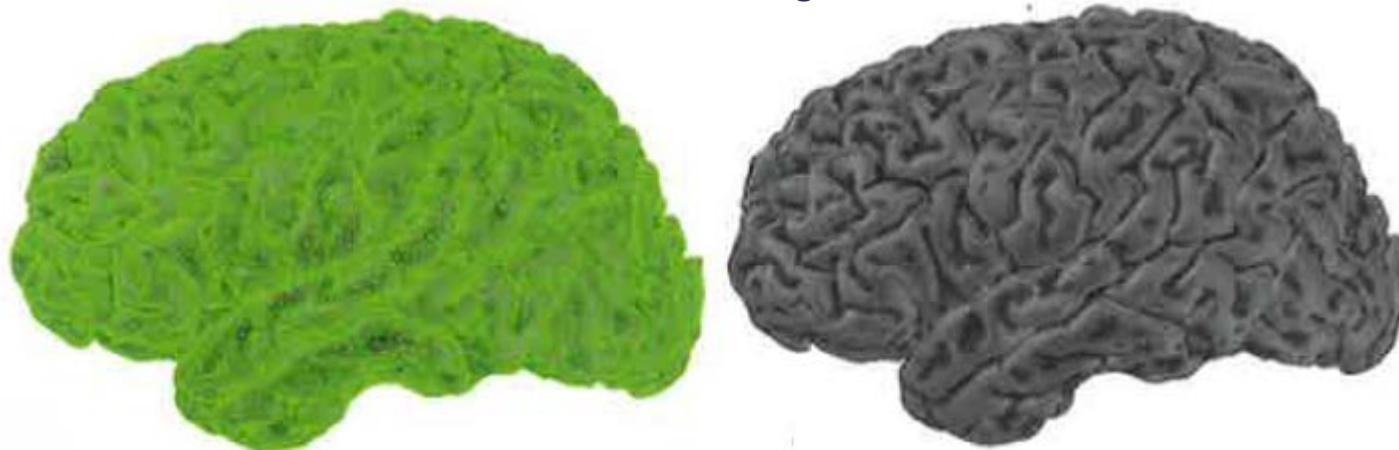
<https://www.sciencedirect.com/science/article/pii/S1053811913010501>

Spatial Sampling of Cortical Surfaces

10.034 vertices, 20.026 triangles of 10 mm² surface area
Sufficient for most EEG/MEG applications

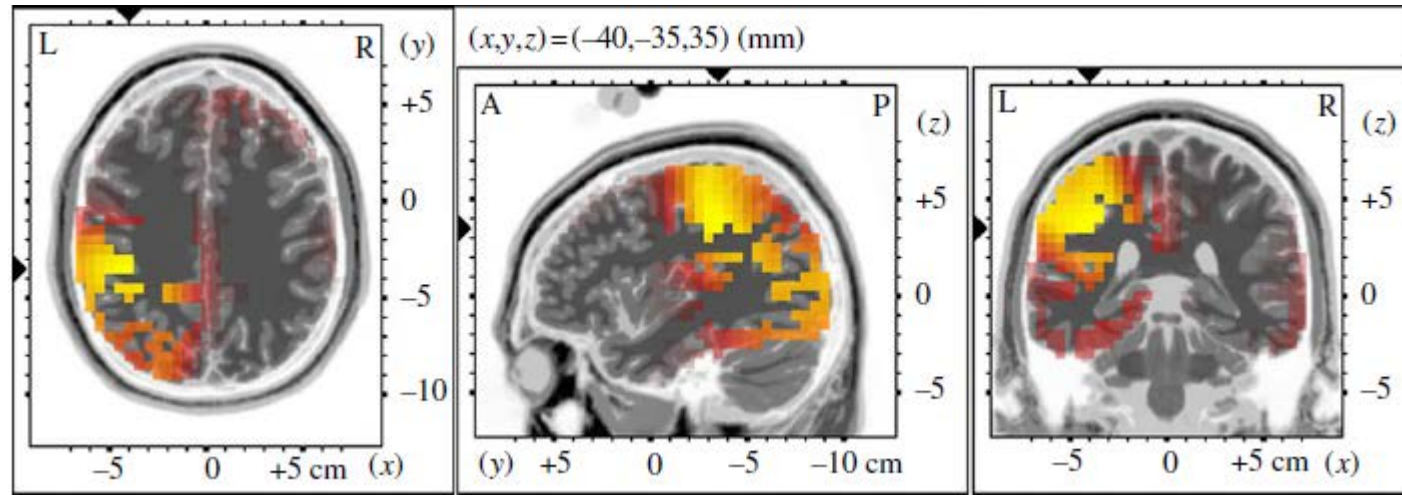


79.124 vertices, 158.456 triangles of 1.3 mm² surface area

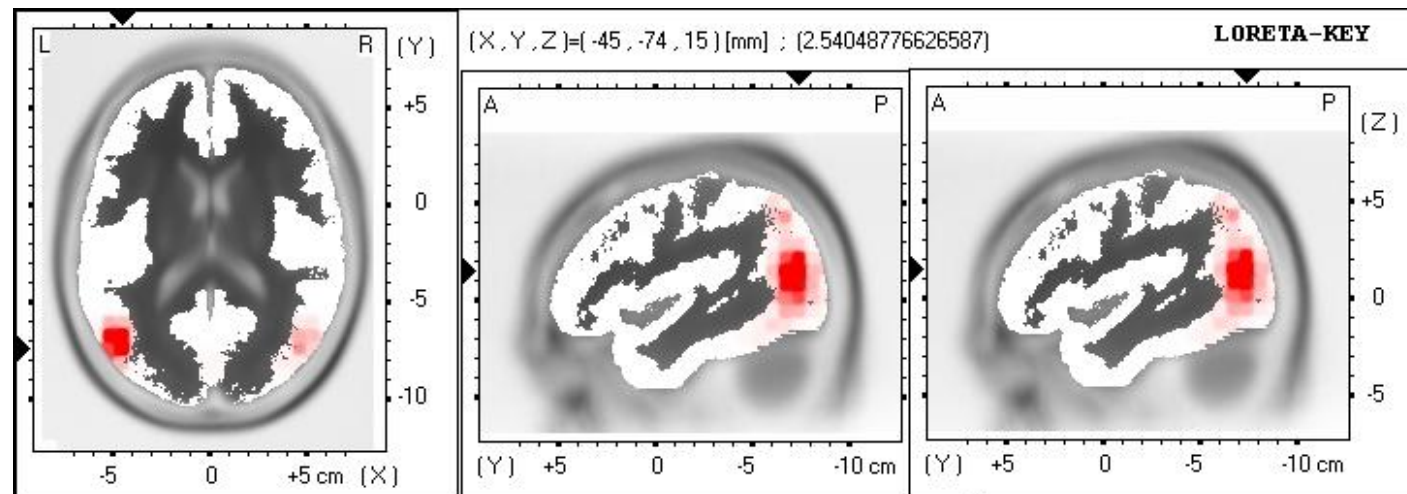


Volumetric Source Spaces Are Possible

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

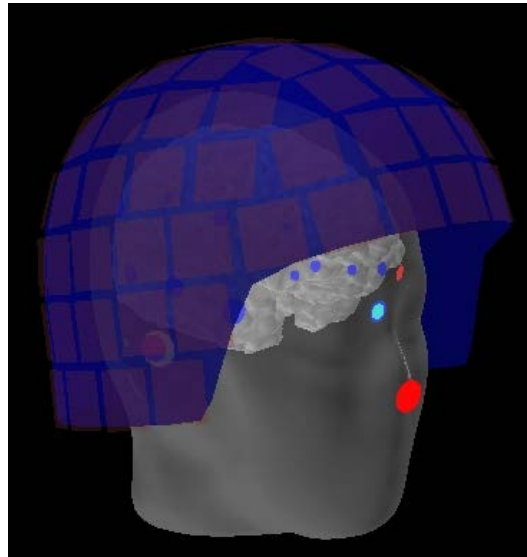


Pascual-Marqui, PTRS-A 2011

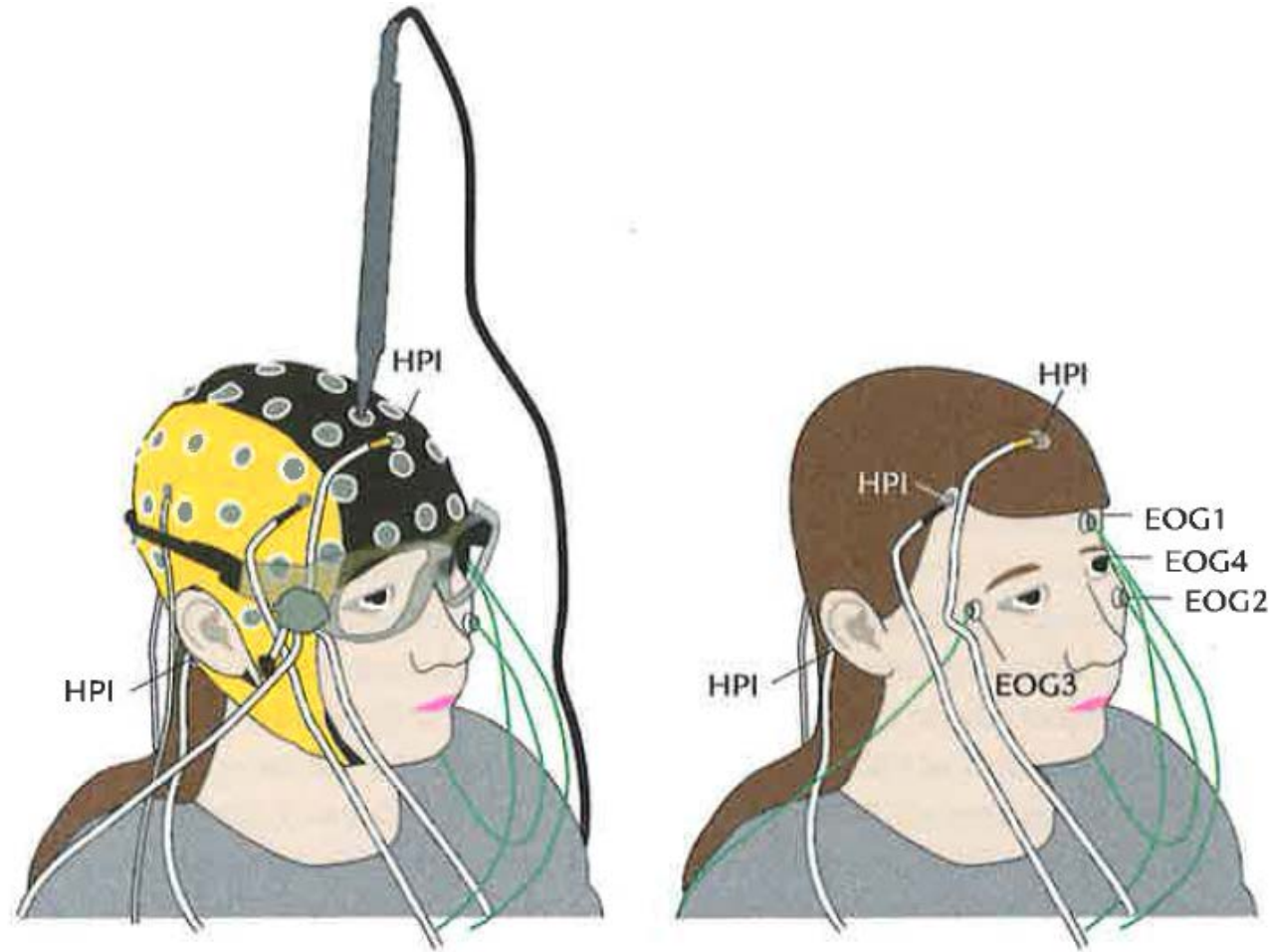


Coregistration of EEG/MEG and MRI Spaces

Coordinate
Transformation



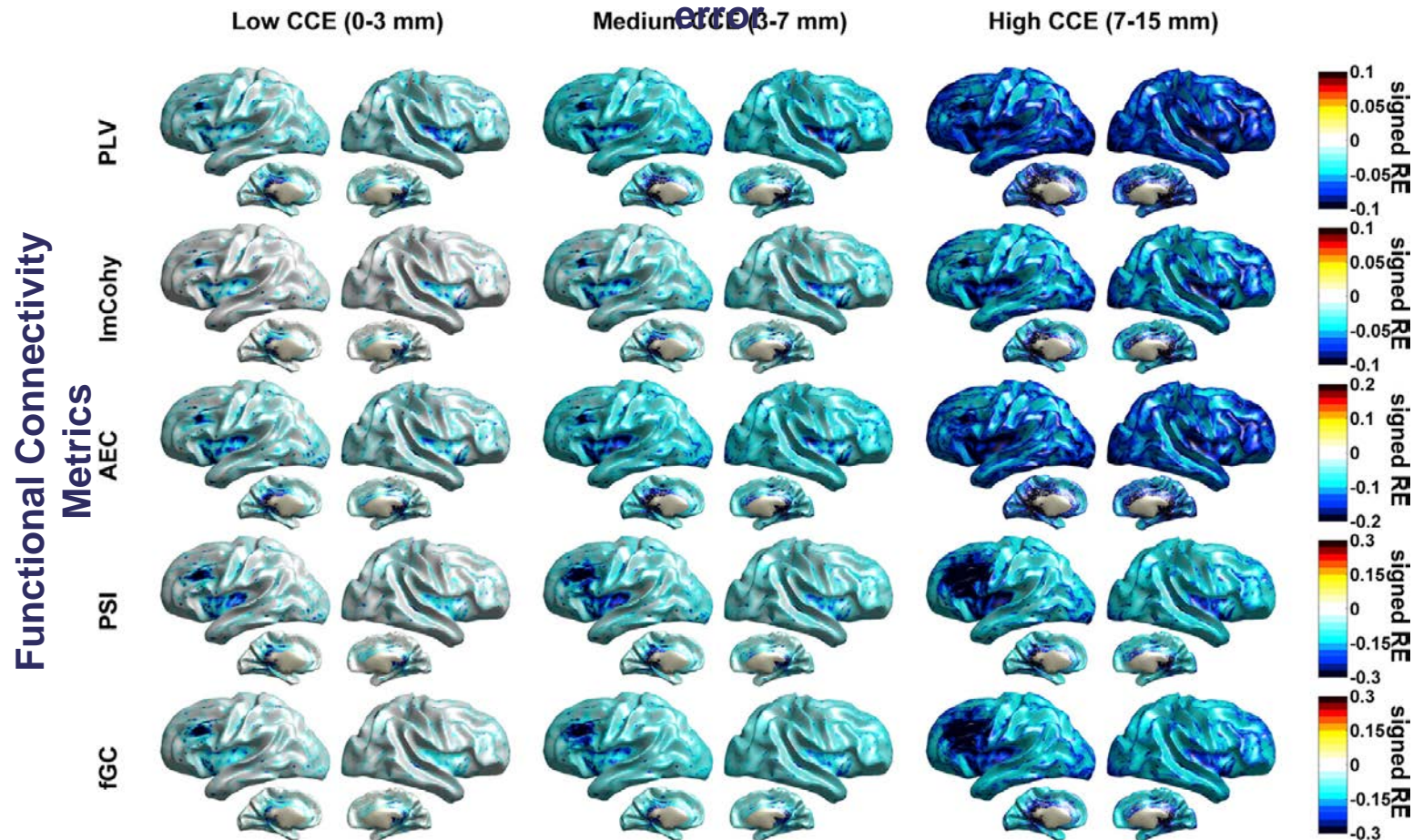
Coregistration of EEG/MEG and MRI Spaces



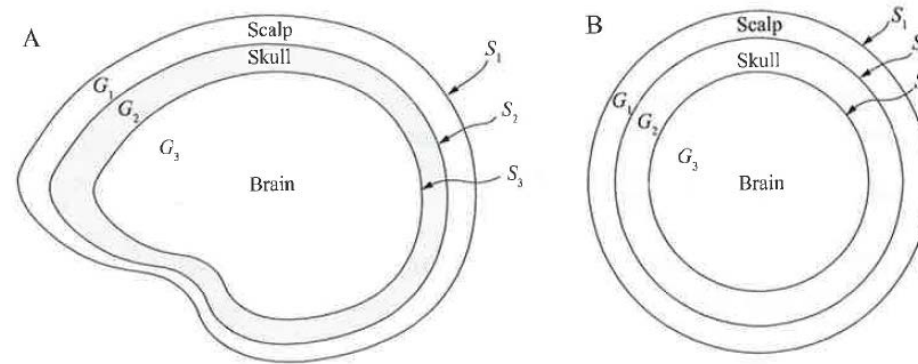
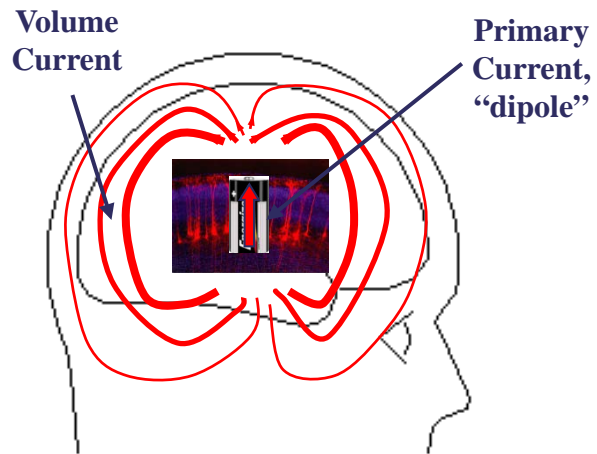
Accurate Coregistration Is Important

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

For example, connectivity analysis:
3 levels of coregistration

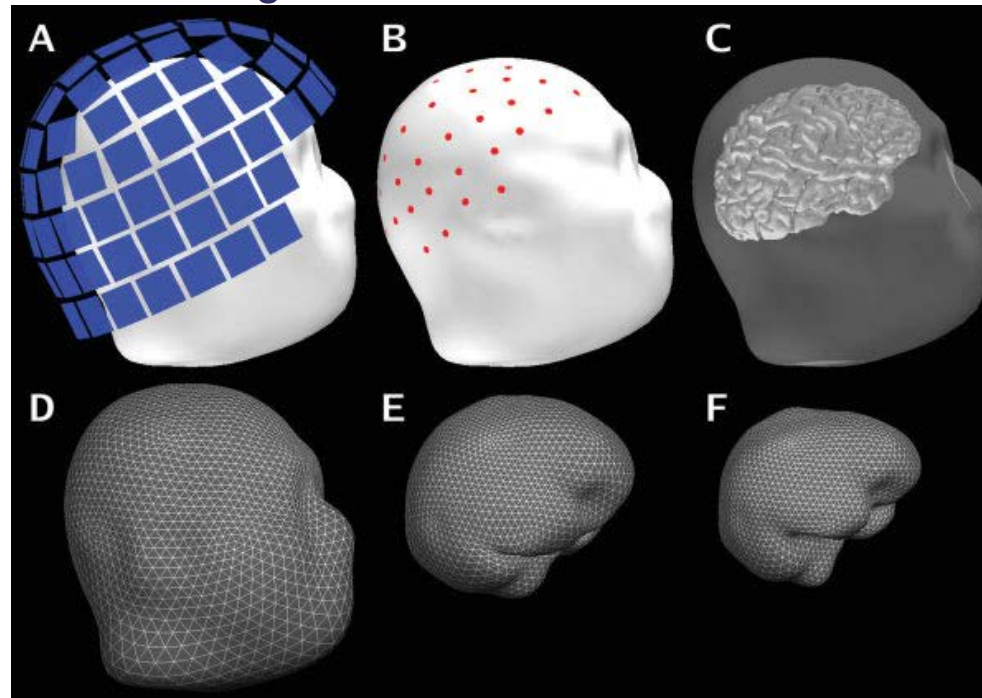


Head Modelling – Tissue Compartments



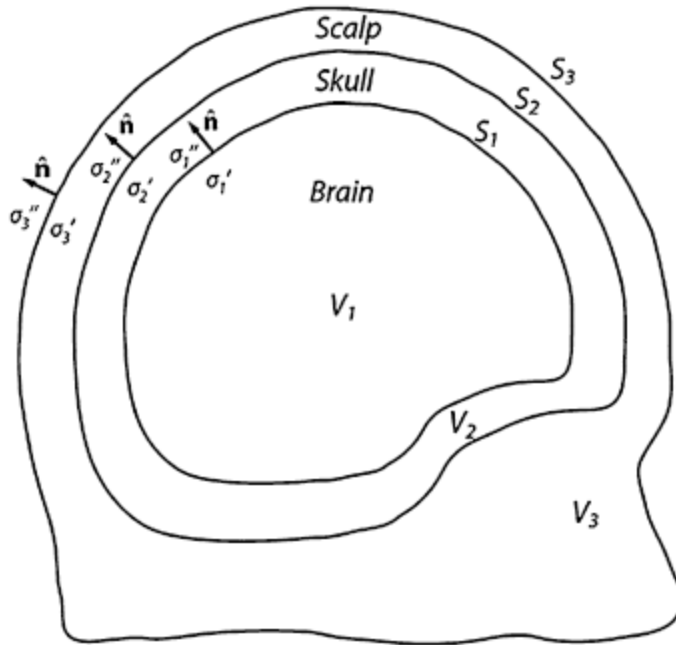
Ilmoniemi and Sarvas, "Brain Signals", MIT 2019

Ingredients for a head model



Goldenholz et al., HBM 2009

BEM: Reducing the Problem to the Boundaries



Electric potential

$$\sigma(\mathbf{r}) V(\mathbf{r}) = \frac{1}{4\pi} \sum_j (\sigma_j' - \sigma_j'') \int_{S_j} dS_j' \mathbf{n}(\mathbf{r}') \cdot \frac{\mathbf{r}' - \mathbf{r}}{|\mathbf{r}' - \mathbf{r}|^3} V(\mathbf{r}') + \frac{1}{4\pi} \int_V d^3r' \mathbf{J}^p(\mathbf{r}') \cdot \frac{\mathbf{r} - \mathbf{r}'}{|\mathbf{r} - \mathbf{r}'|^3},$$

Magnetic Field

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

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

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

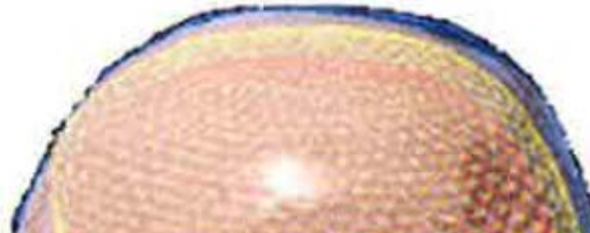
- Volume currents depend on conductivity distribution within the whole head volume.
- EEG measurements on the scalp depend on volume currents, and are strongly affected by head geometry.
- MEG measurements are the sum of magnetic fields from primary and volume currents, but the magnetic fields of currents 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.

Head Models With Different Levels of Detail

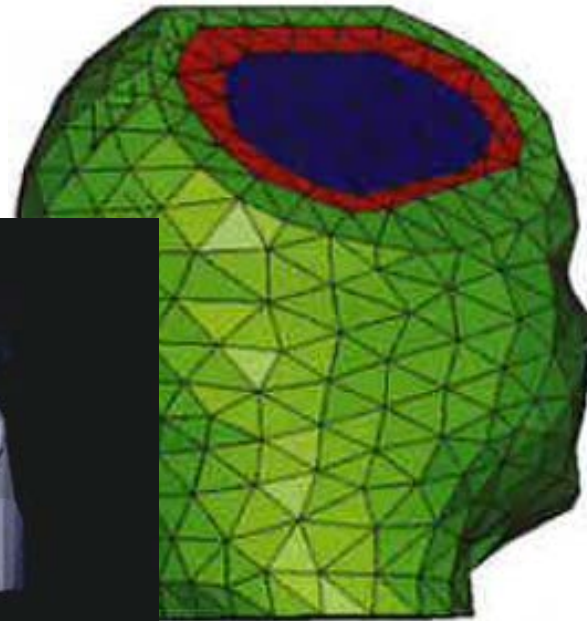
Spheres



Boundary Element Model
(BEM)



Finite Element Model
(FEM)



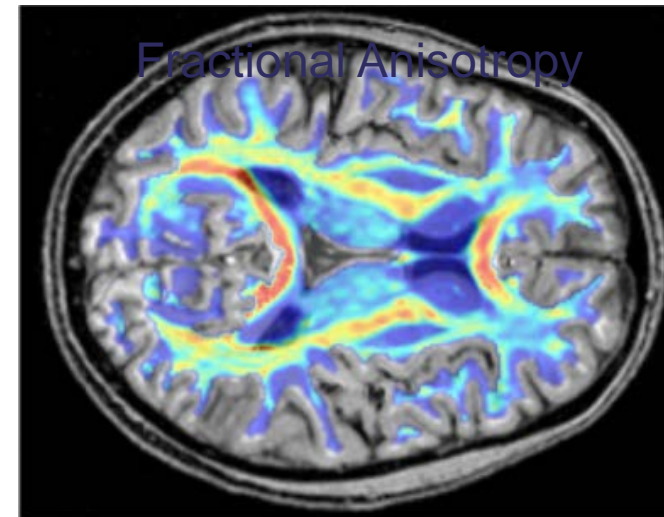
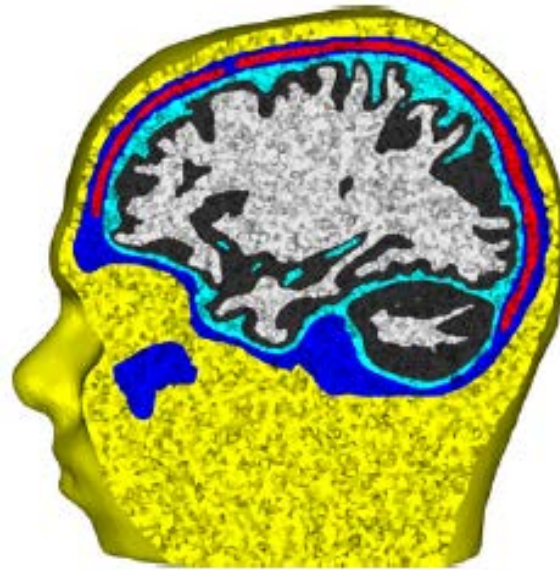
More Complex Head Models

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
Compakta
Skull
Spongiosa
Skin



Vorwerk et al., NI 2014

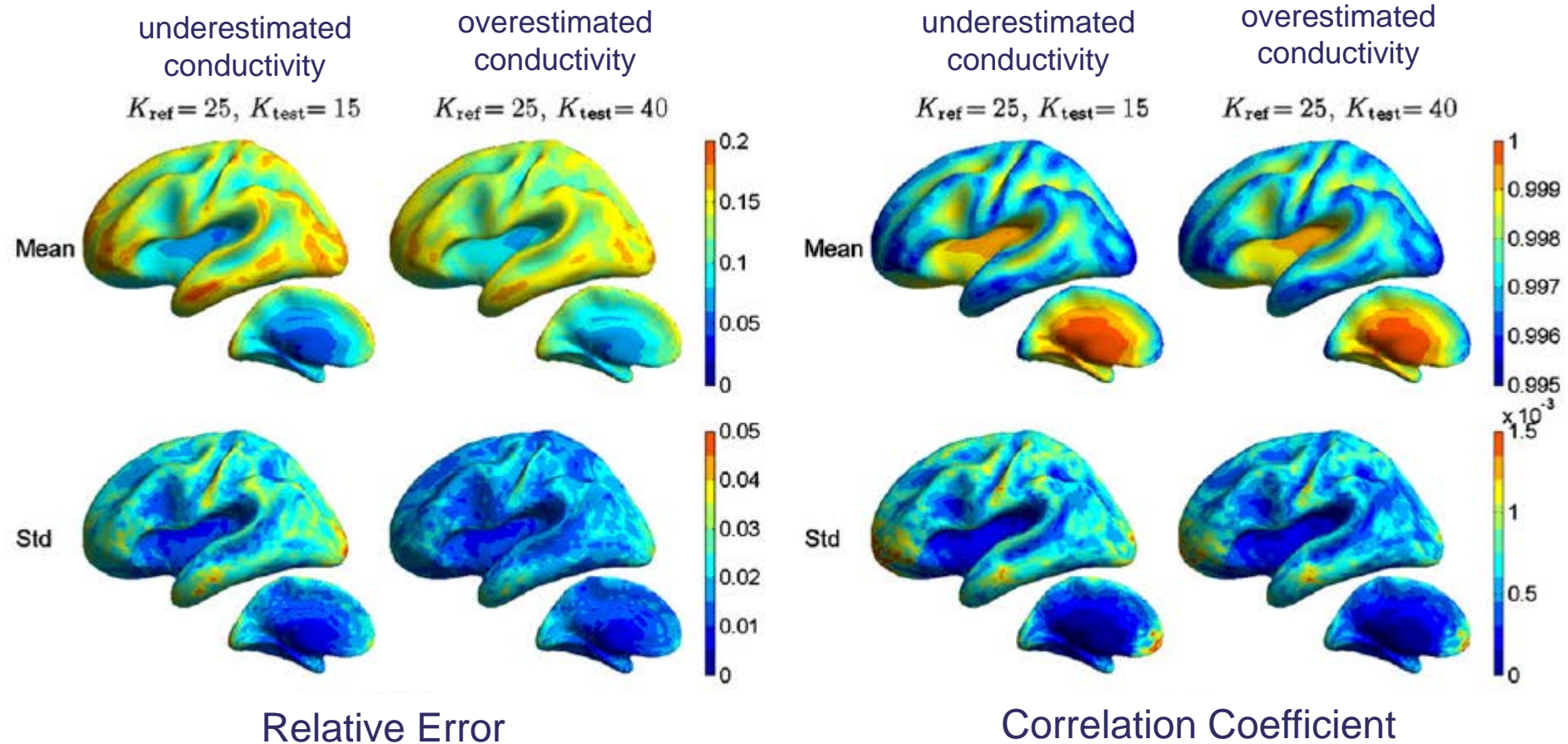
It is not obvious how to translate this into more accurate estimate for conductivity distributions.

Conductivities Of Tissues Can Only Be Approximated

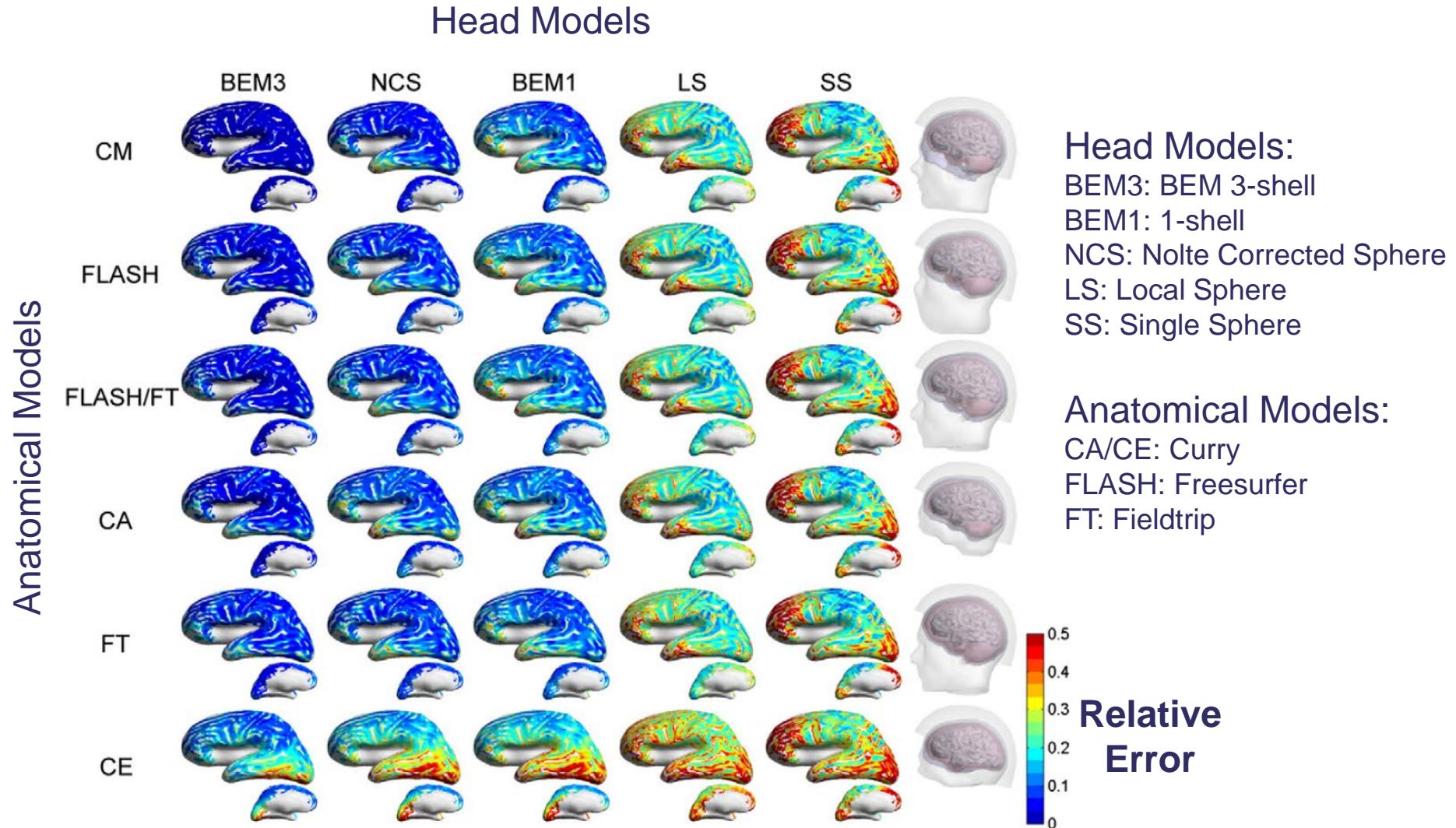
Table 2 Isotropic conductivity values of single tissue types used in human head volume conductor modeling

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

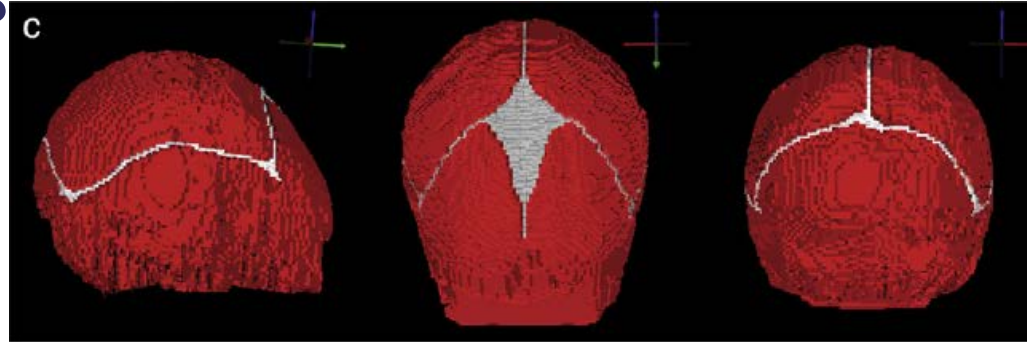
Boundary Element Models Are Relatively Robust Against Conductivity Errors



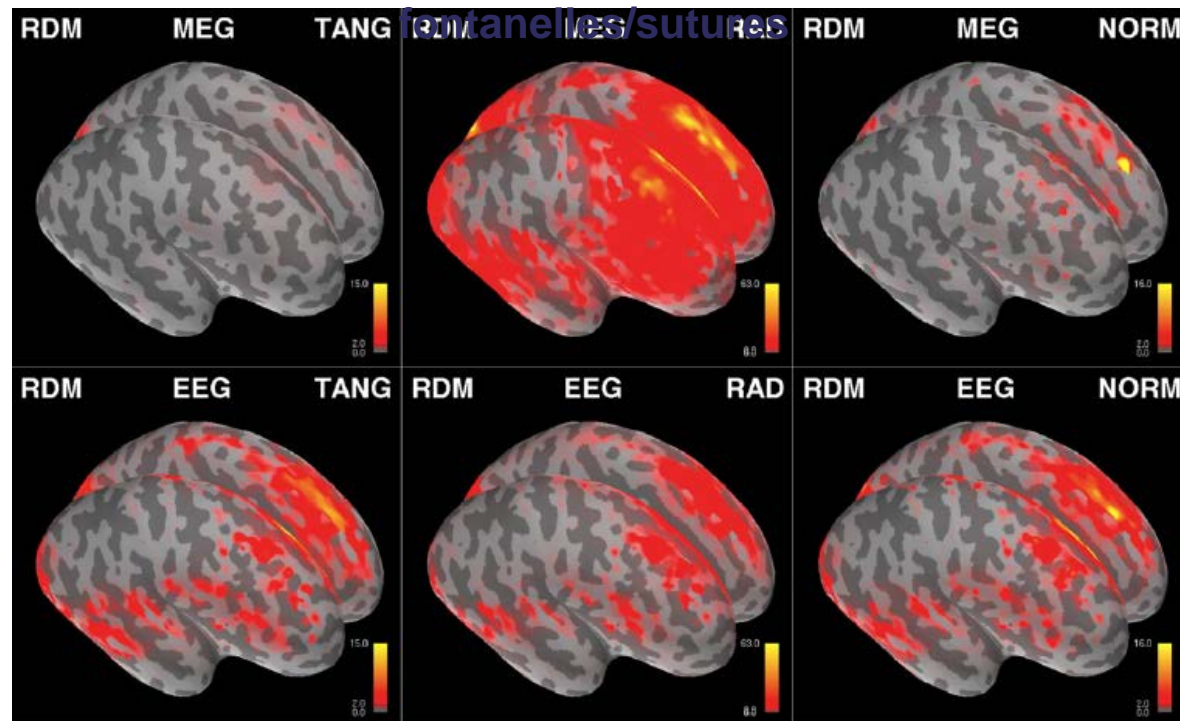
The Effect of Head Model Accuracy for MEG



Infant Skulls – Fontanelles and Sutures



Relative error between models with and without



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