Physiological Basis of EEG/MEG Signals, Forward Models and Source Reconstruction

Will Penny

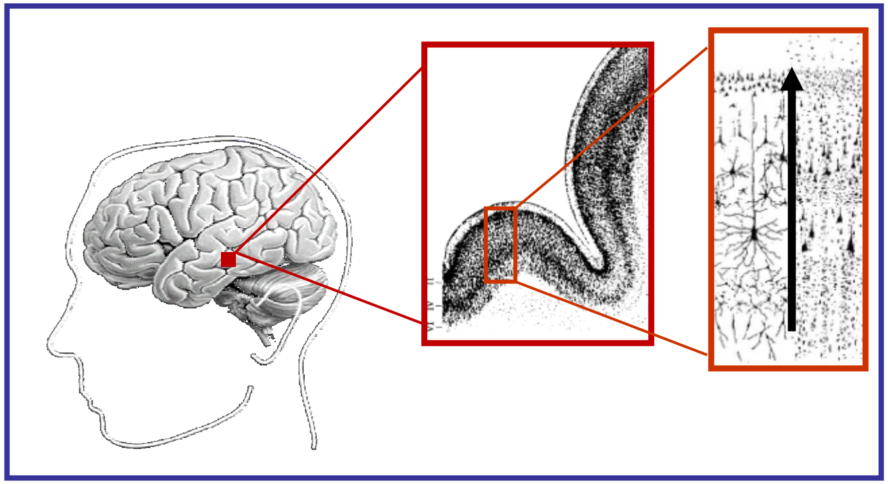
Wellcome Trust Centre for Neuroimaging,
University College London, UK

MSc Advanced Neuroimaging, Dec 2, 2008

Content

- Neural activity
- Forward models
- Source reconstruction

Physiological sources



MEG/EEG signals derive primarily from cortical current sources

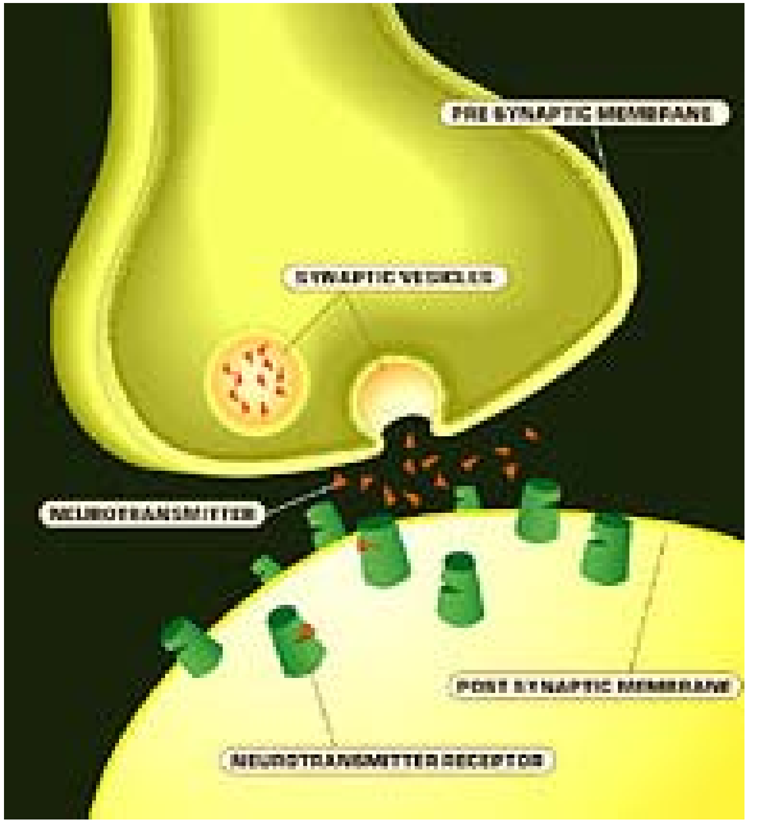
Strong, focal subcortical activity can also give rise to MEG/EEG

Action potentials and synapses

- After an action potential is received neurotransmitters are released

- They bind to the receptors of a postsynaptic neuron creating Post-Synaptic Potentials (PSPs)

- These are caused by ions flowing in and out of postsynaptic membrane (eg Cl)

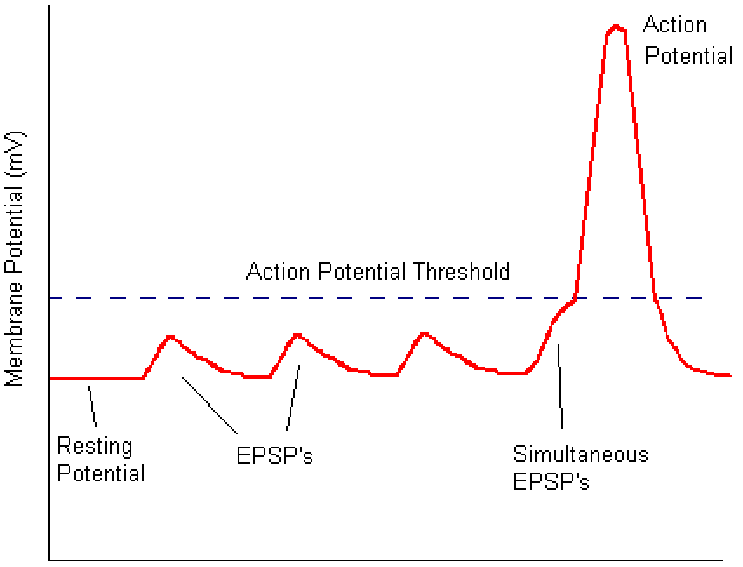


Postsynaptic potentials

Na ions in,
K ions out

- Depending on whether the neurotransmitter is excitatory or inhibitory, **electrical current flows** from the postsynaptic cell to the environment, or the opposite

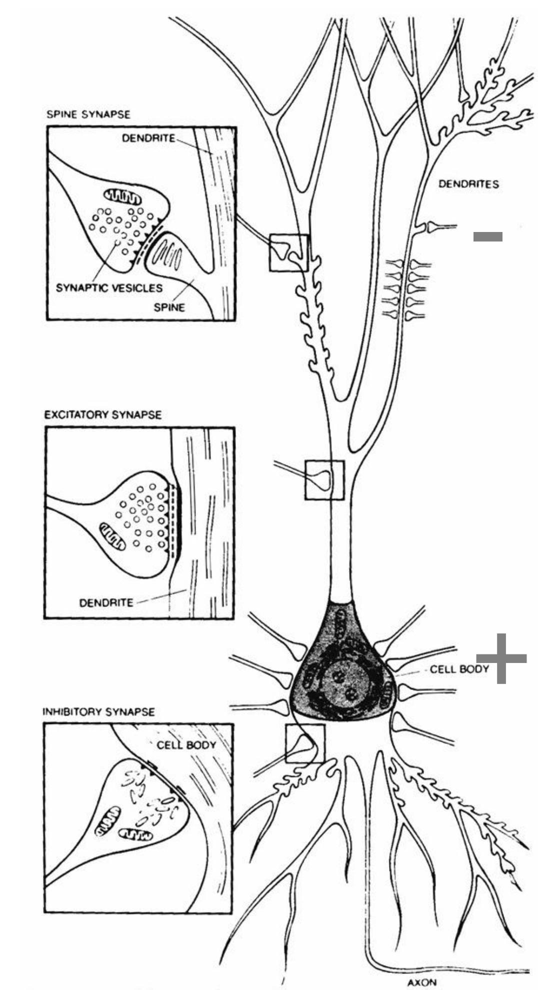
- The membrane of the postsynaptic cell becomes depolarised (more likely to generate an action potential) or hyperpolarised (less likely to generate an action potential)



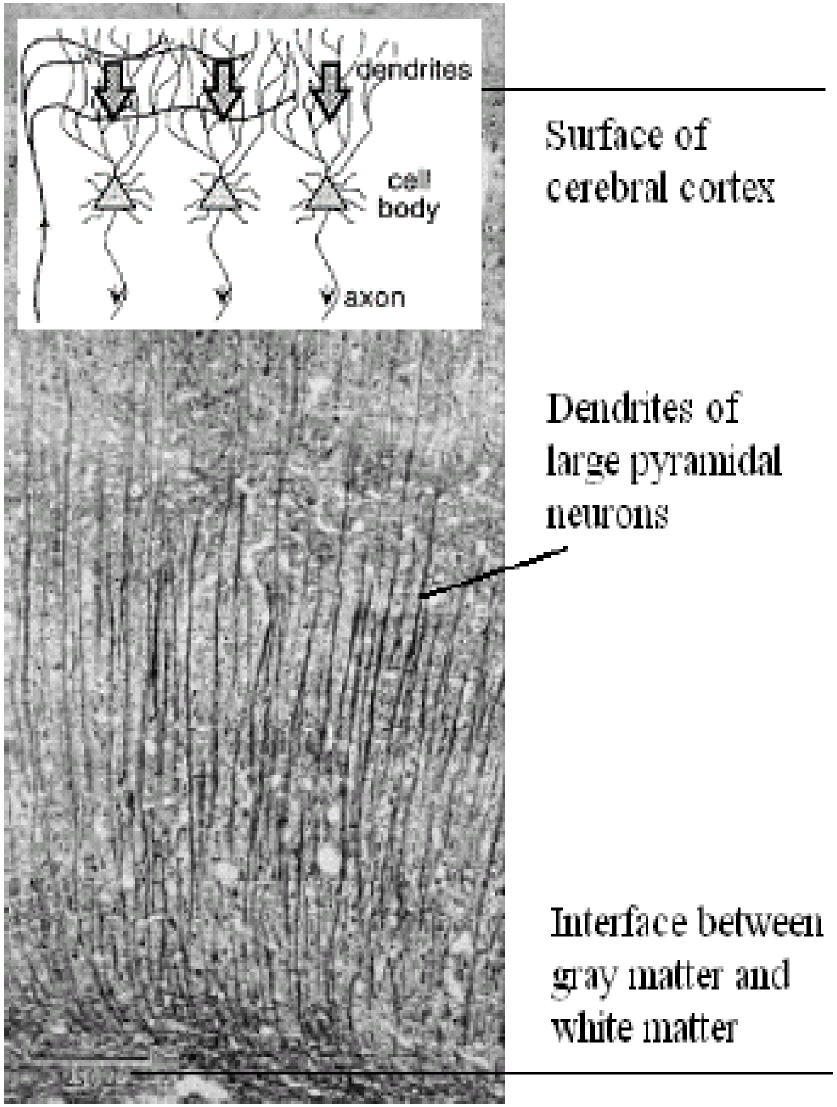
Action potentials not picked up by EEG/MEG

Primary current

- Negative ions flowing out of cell and positive ions into it, make cell +ve voltage
- PSP effects last tens to hundreds of milliseconds
- Postsynaptic potentials of neighboring cells can be similar (ensemble encoding).

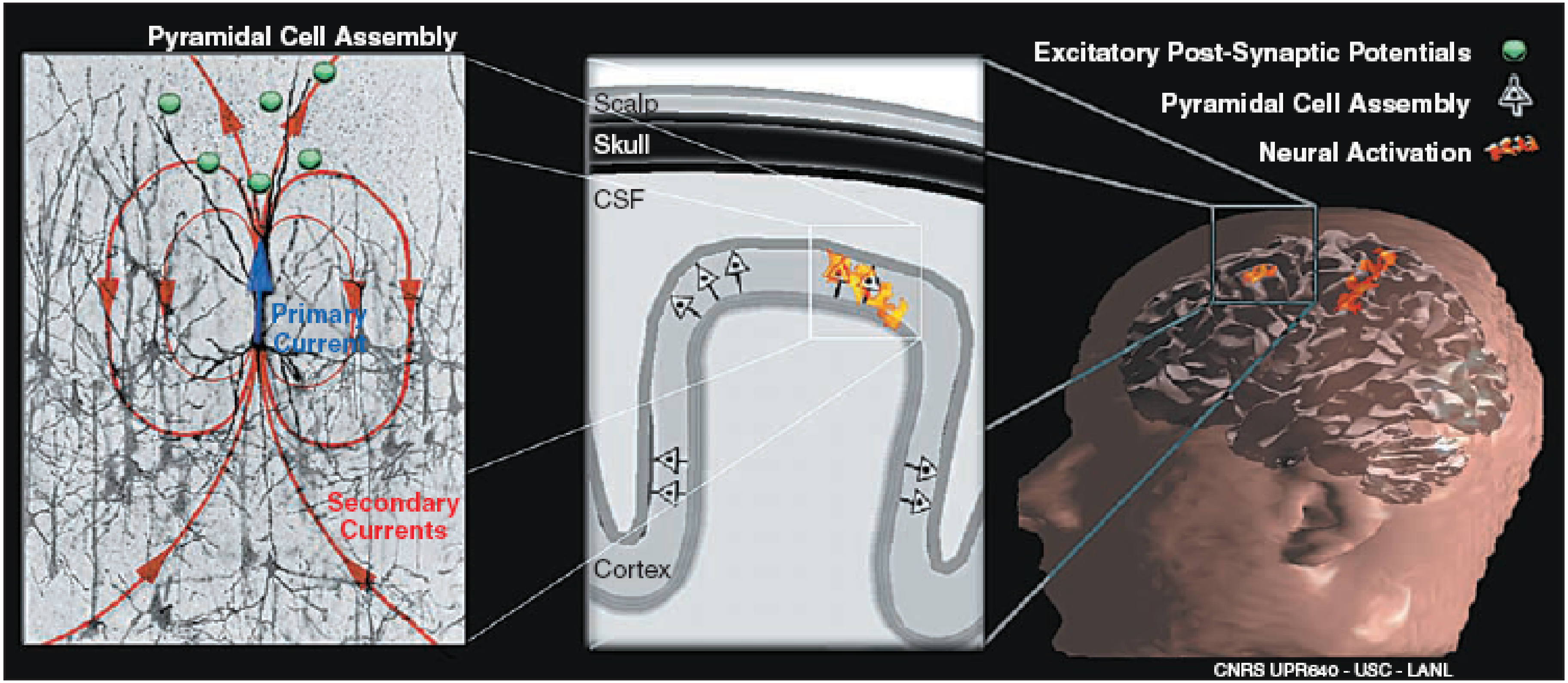


Cortical sheet



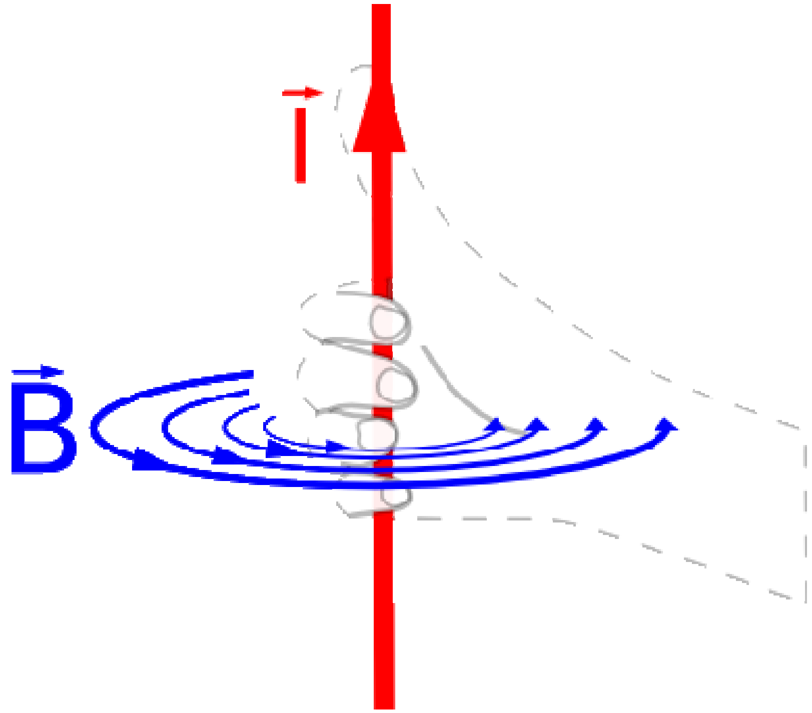
- Pyramidal neurons of the cortex are spatially aligned and perpendicular to the cortical surface
- Spatial and temporal alignment of membrane potential creates dipoles
- Action potential are not sufficiently correlated over space and time to contribute to dipoles

Dipoles



- Primary current, J_p =dipole
- Secondary current, J_v = volume current (Ohmic return current caused by dipole)
- MEG is sensitive to primary and volume currents
- EEG is sensitive to volume currents

Right hand rule



Magnetic field, B, induced by primary current vector
Also, field induced by volume currents

Content

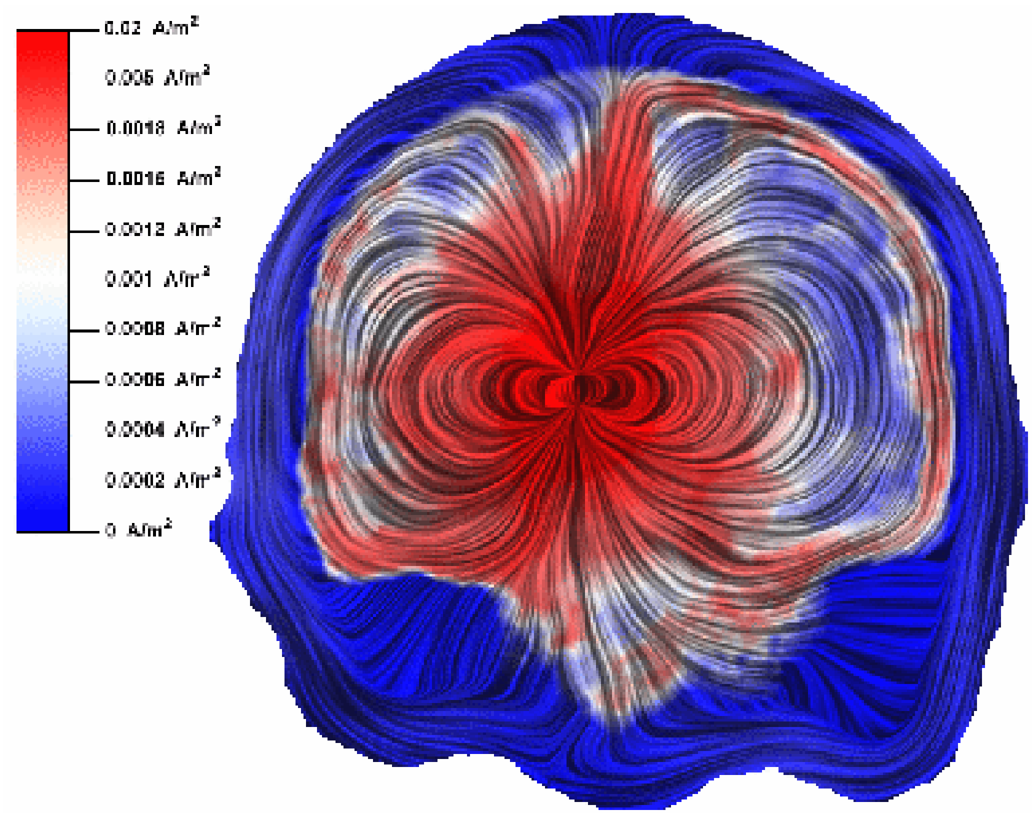
- Neural activity
- Forward models
- Source reconstruction

Volume conduction

- When a dipole is in a conductive medium, electrical current spreads through this medium (the ‘volume’ or ‘secondary’ currents). They reach the scalp to induce the voltage differences that EEG is sensitive to.

- Brain, skull and scalp have different conductivities

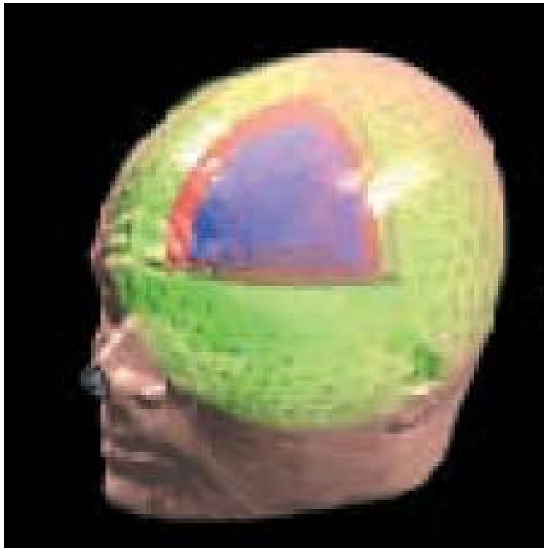
- The skull has a higher electrical resistance than the brain => the electrical signal spreads laterally when reaching the skull



Volume currents for a thalamic dipole source computed using a finite element volume conductor model (see later).

Spherical head model

• Approximate the shape and electromagnetic properties of the head using a three concentric sphere model



• For brain, skull, and scalp

• Assume homogeneous conductivity in each sphere

• The potential on the scalp (and each surface) can be computed analytically by solving the quasi-static (freq<1kHz) approximation of Maxwell’s equations.

Forward solution for EEG

Potential at r due to primary current

$$V_0(r) = \frac{1}{4\pi\sigma_0} \int J_p(r').\frac{r-r'}{\|r-r'\|^3} \; dr'$$

Solve following equation for potentials on all surfaces, V(r)

$$(\sigma_i + \sigma_j)V(r) = 2\sigma_0 V_0(r) - \frac{1}{2\pi}\sum_{ij}(\sigma_i - \sigma_j)\int_{S_{ij}} V(r')\frac{r-r'}{\|r-r'\|^3} \; dS_{ij}'$$

The latter sums are surface integrals of over brain-skull, skull-scalp and scalp-air boundaries

Forward solution for MEG

Magnetic field at (vector) position r due to all primary (vector) currents

$$B_0(r) = \frac{\mu_0}{4\pi} \int J_p(r') \times \frac{r - r'}{\left\| r - r' \right\|^3} \; dr'$$

Magnetic field at position r due to volume currents

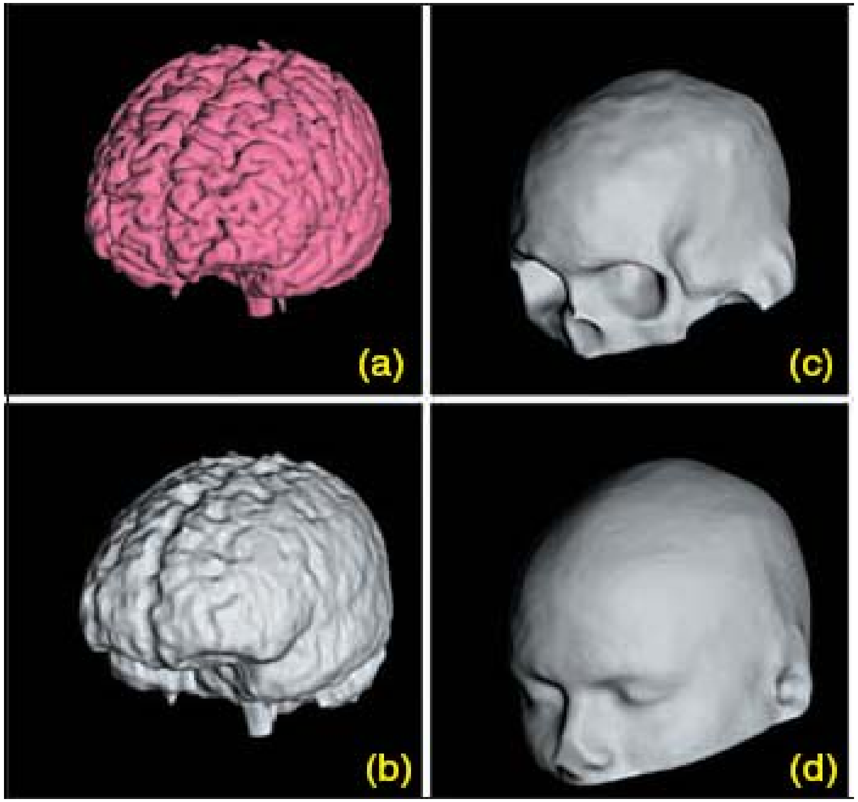
$$B_v(r) = \frac{\mu_0}{4\pi} \sum_{ij} \left(\sigma_i - \sigma_j \right) \int_{S_{ij}} V(r') \frac{r - r'}{\left\| r - r' \right\|^3} \times dS_{ij}$$

The latter sums are surface integrals of current over brain-skull, skull-scalp and scalp-air boundaries, which require voltage distribution over each surface (ie. EEG forward solution). The total magnetic field is given by

$$B(r) = B_0(r) + B_v(r)$$

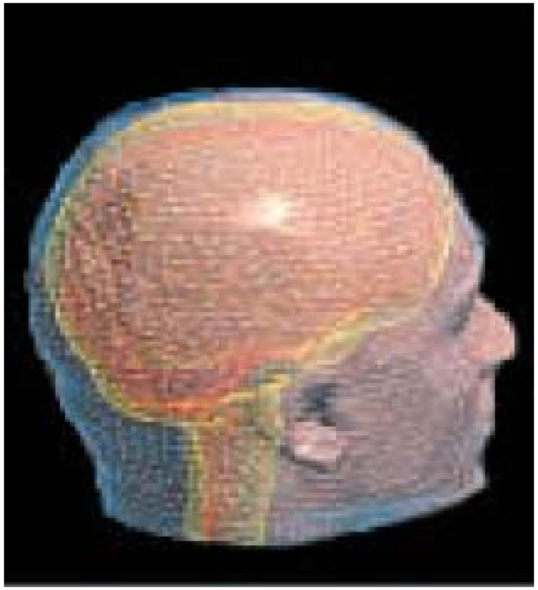
Boundary element model

Brain Skull



Brain (smoothed) Scalp

BEM



Boundaries between brain, skull, scalp modelled using MRI data

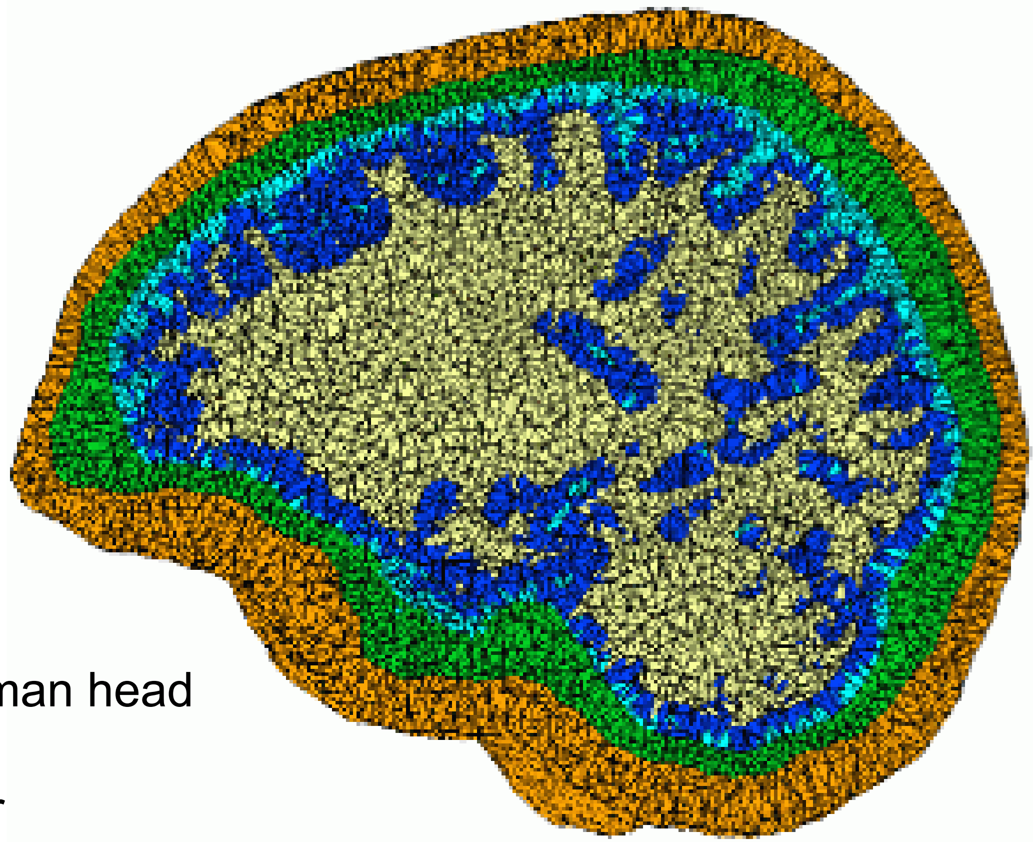
Assumes homogeneous conductivity in each partition

Finite element head model

Five compartments (scalp, skull, CSF, brain grey and white matter)
Many thousand elements in each with different conductivity.

Diffusion Tensor Imaging data used for estimation of gray/white matter conductivity.

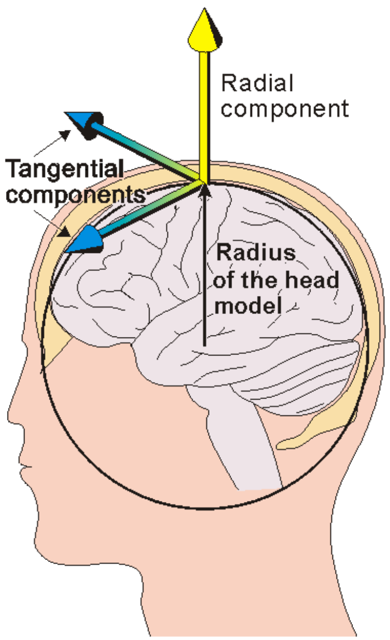
Also use of Electrical Impedance Tomography (EIT)

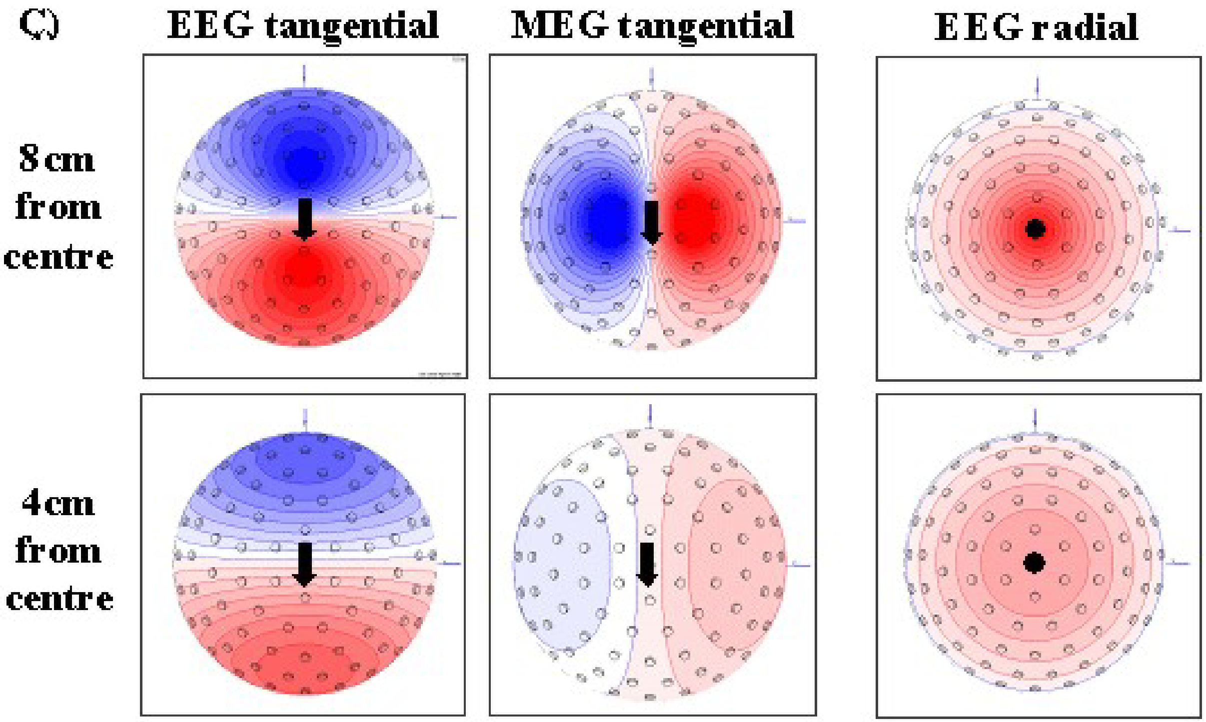


Sagittal cut through Finite Element volume conductor model of the human head

Spherical head models are a better approximation for MEG than EEG because MEG is also sensitive to primary currents

Tangential and radial dipoles

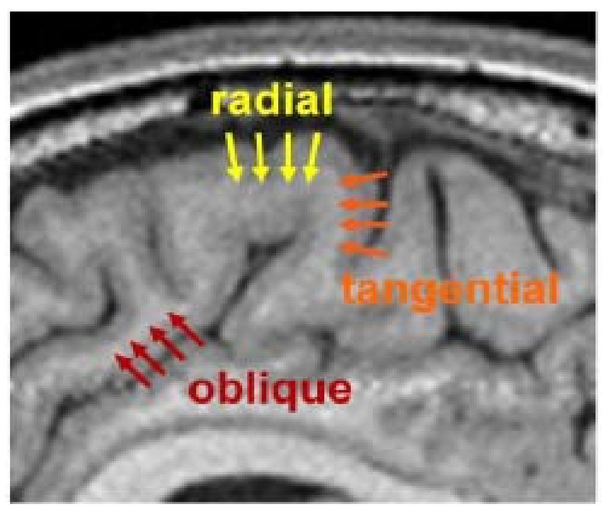


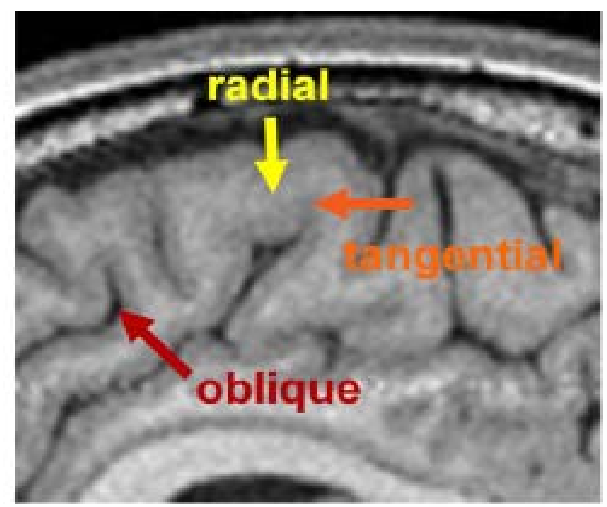


Tangential dipole is oriented parallel to the cortical surface

Radial dipole is oriented towards or away from it

MEG is not sensitive to radial dipoles





Lower amplitude closer to centre of head (bigger reduction for MEG)

Content

- Neural activity
- Forward models
- Source reconstruction

Equivalent Current Dipole (ECD) Source Reconstruction

Assume a small number of dipoles, typically less than ten, perhaps bilateral.

For each estimate 6 parameters, a, (x,y,z location, 2 direction, 1 strength)

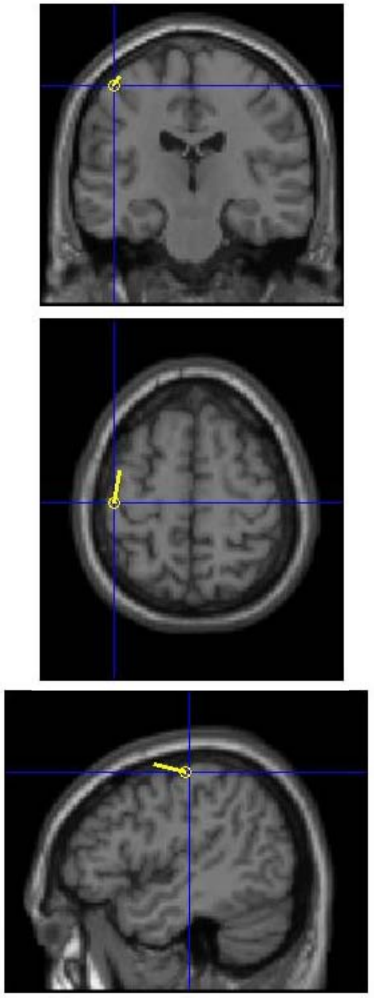
data points= # sensors x # time points

Small number of parameters compared to amount of data (good)

Optimisation problem is highly nonlinear (bad)

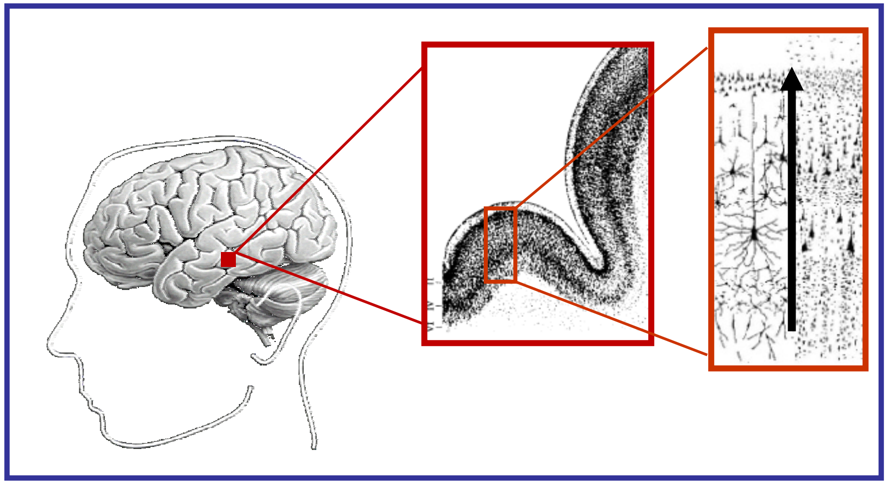
MEG data, y=f(a)+e.

May need prior information to seed optimisation



Distributed Source Reconstruction

A. Cortical Sources



$$Y = KJ + E$$

data — gain matrix — dipole amplitudes — noise

From an MRI, create a cortical mesh with eg. 3000 vertices.

Place a dipole perpendicular to cortical surface at each vertex

For each dipole, we only need to estimate the strength, j

The sensor dipolar patterns seen earlier form columns in a gain or ‘lead field’ matrix K.

MEEG/EEG data in column vector y. To find sources, need to solve a linear optimisation problem (good)

But we have fewer sensors than sources (bad). Constraints needed.

ECD vs Distributed

Typically ECD methods are used to estimate early components of ERPs which are usually highly localised

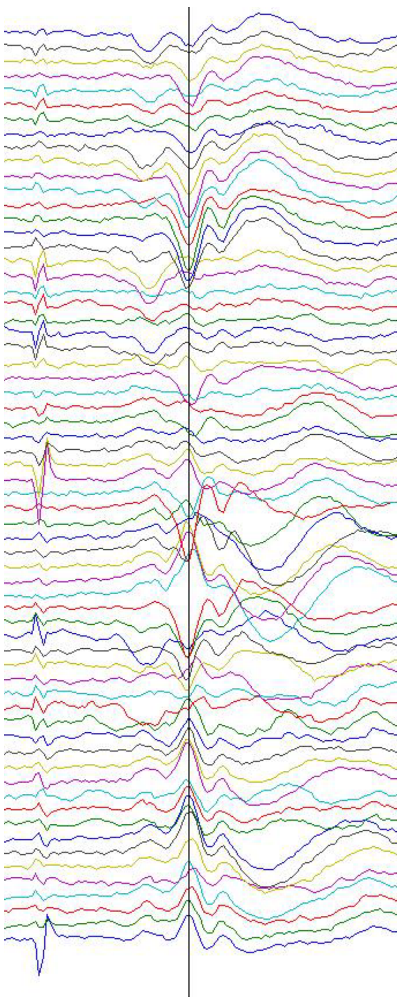
ECD methods useful for subcortical reconstruction.

Distributed solutions are used for reconstructing later components of ERPs. These more cognitive components are often highly distributed throughout cortex.

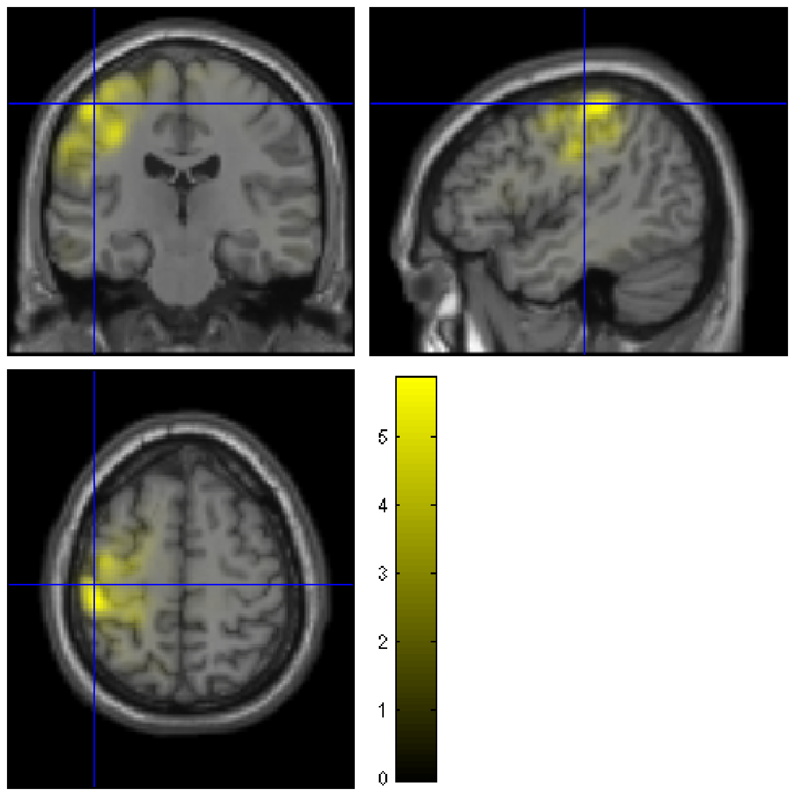
There are also distributed solutions for volumes. Unlike distributed source solutions for cortical meshes we also need to estimate direction of dipoles (implemented by estimating current strength in x,y,z directions).

EEG Data: Somatosensory Stimulation

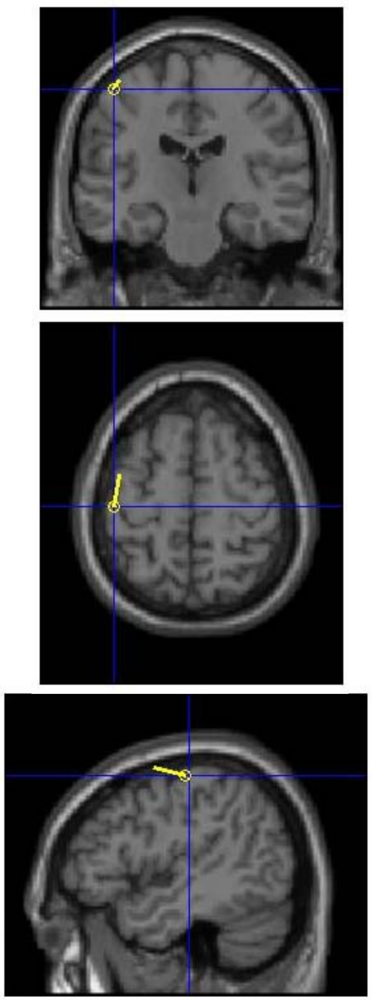
Scalp distribution
21ms post-stimulus



Distributed Source Reconstruction

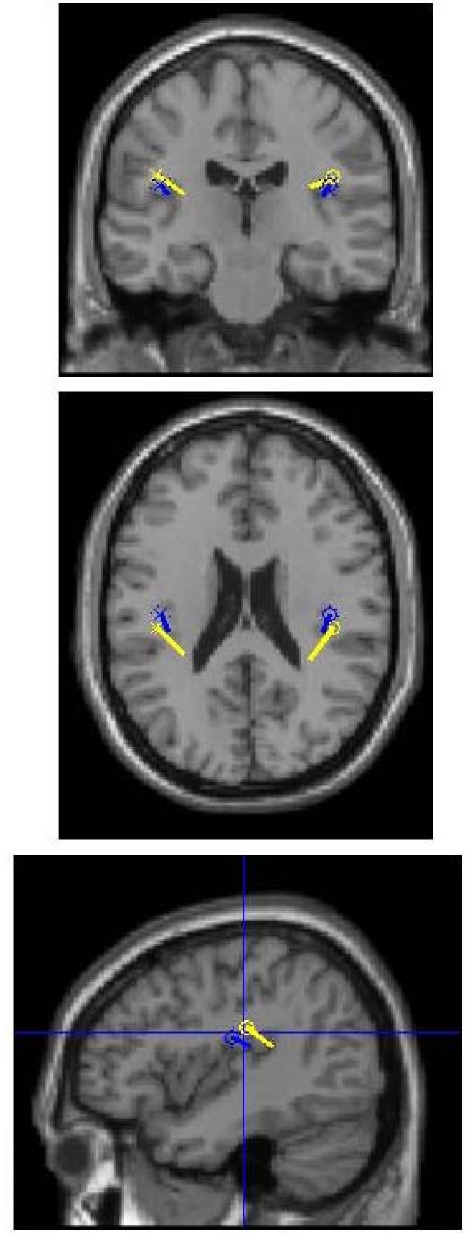


ECD

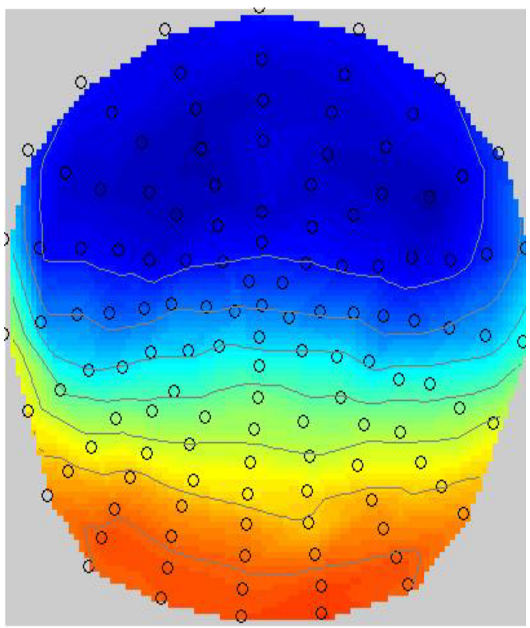


EEG Data: Auditory Oddball

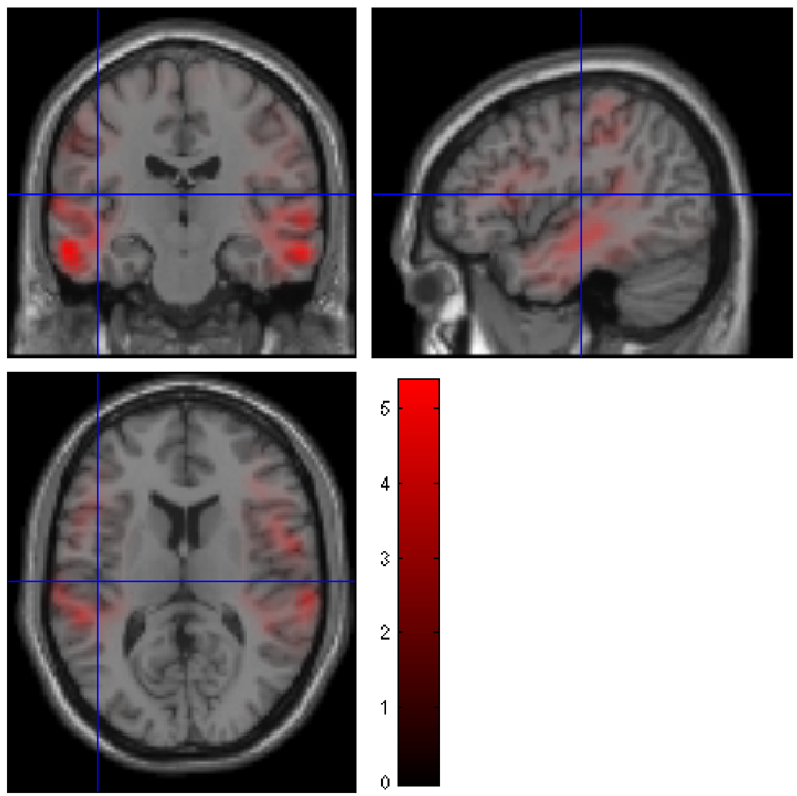
ECD



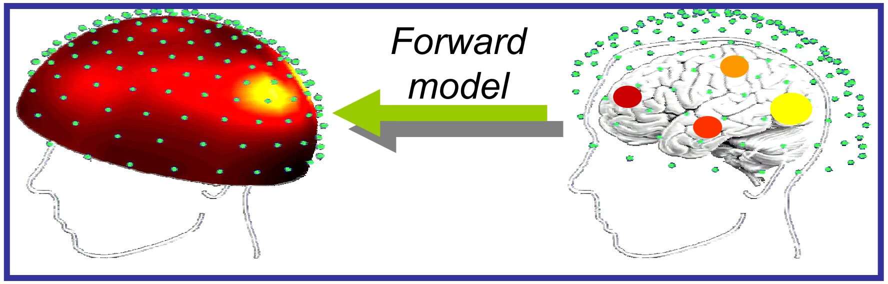
Scalp potential



Distributed Source Reconstruction

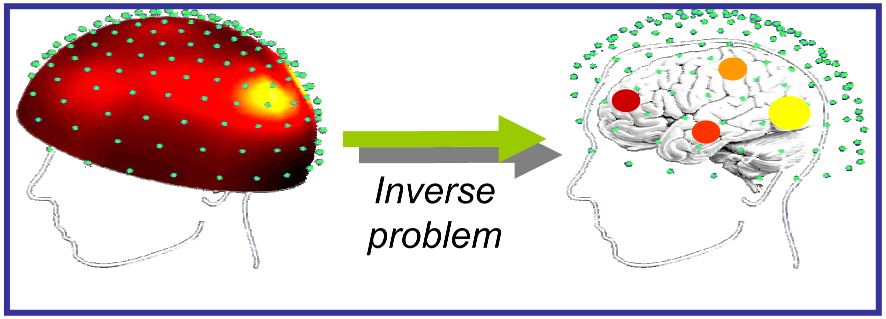


Bayesian Source Reconstruction



$$p(\mathbf{Y} \mid \mathbf{J}, \mathcal{M})$$

likelihood



$$p(\mathbf{J} \mid \mathbf{Y}, \mathcal{M})$$

posterior

likelihood prior

$$p(\mathbf{J} \mid \mathbf{Y}, \mathcal{M}) = \frac{p(\mathbf{Y} \mid \mathbf{J}, \mathcal{M})\, p(\mathbf{J} \mid \mathcal{M})}{p(\mathbf{Y} \mid \mathcal{M})}$$

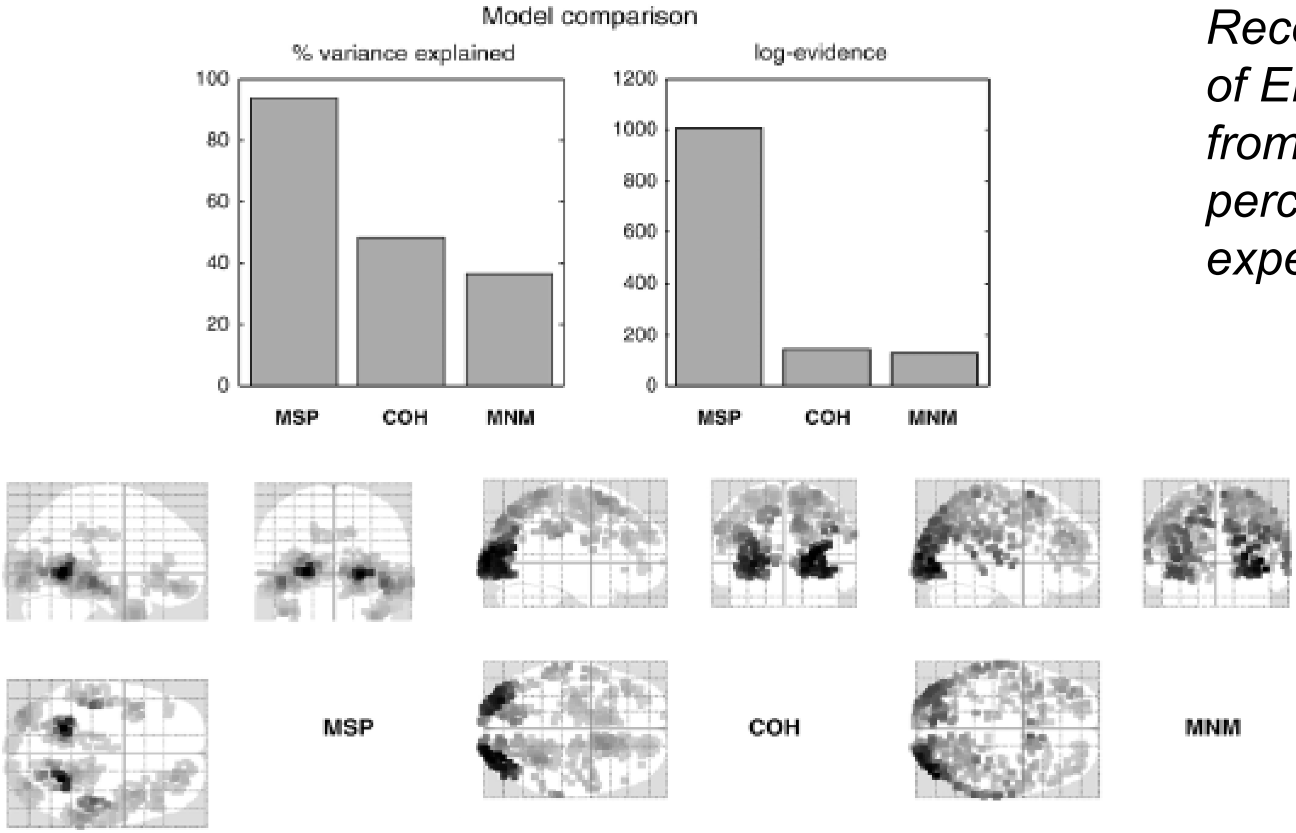
posterior

evidence

Bayesian Source Reconstruction

- Formal statistical comparison of constraints (priors) used in distributed source reconstruction methods, using model evidence
- Multiple Sparse Priors (MSP)
- Flexible models that can be intermediate between ECD and distributed solutions

Distributed source solutions with different constraints



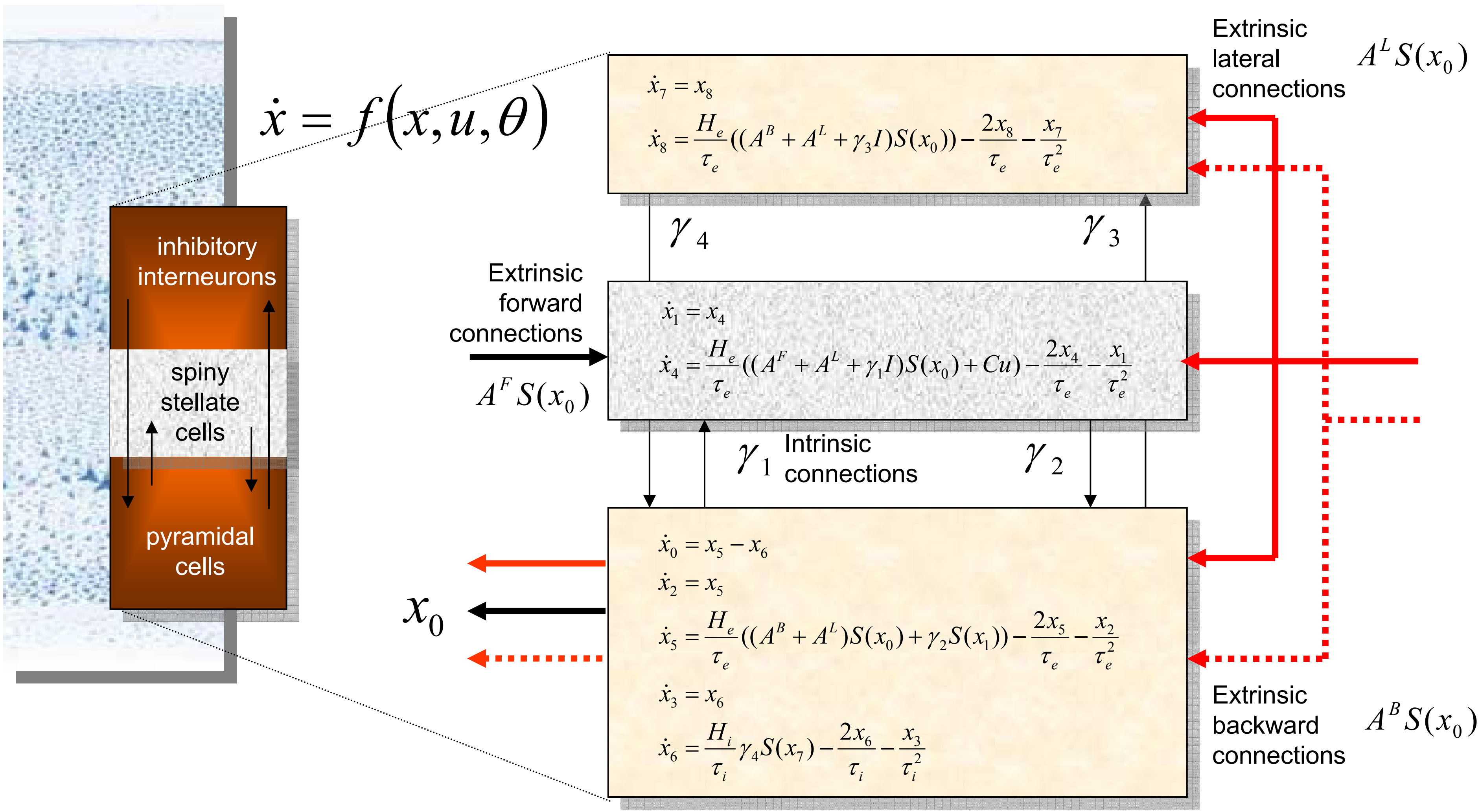
Reconstruction of EEG data from face perception experiment

Multiple Sparse Priors

Spatial Coherence

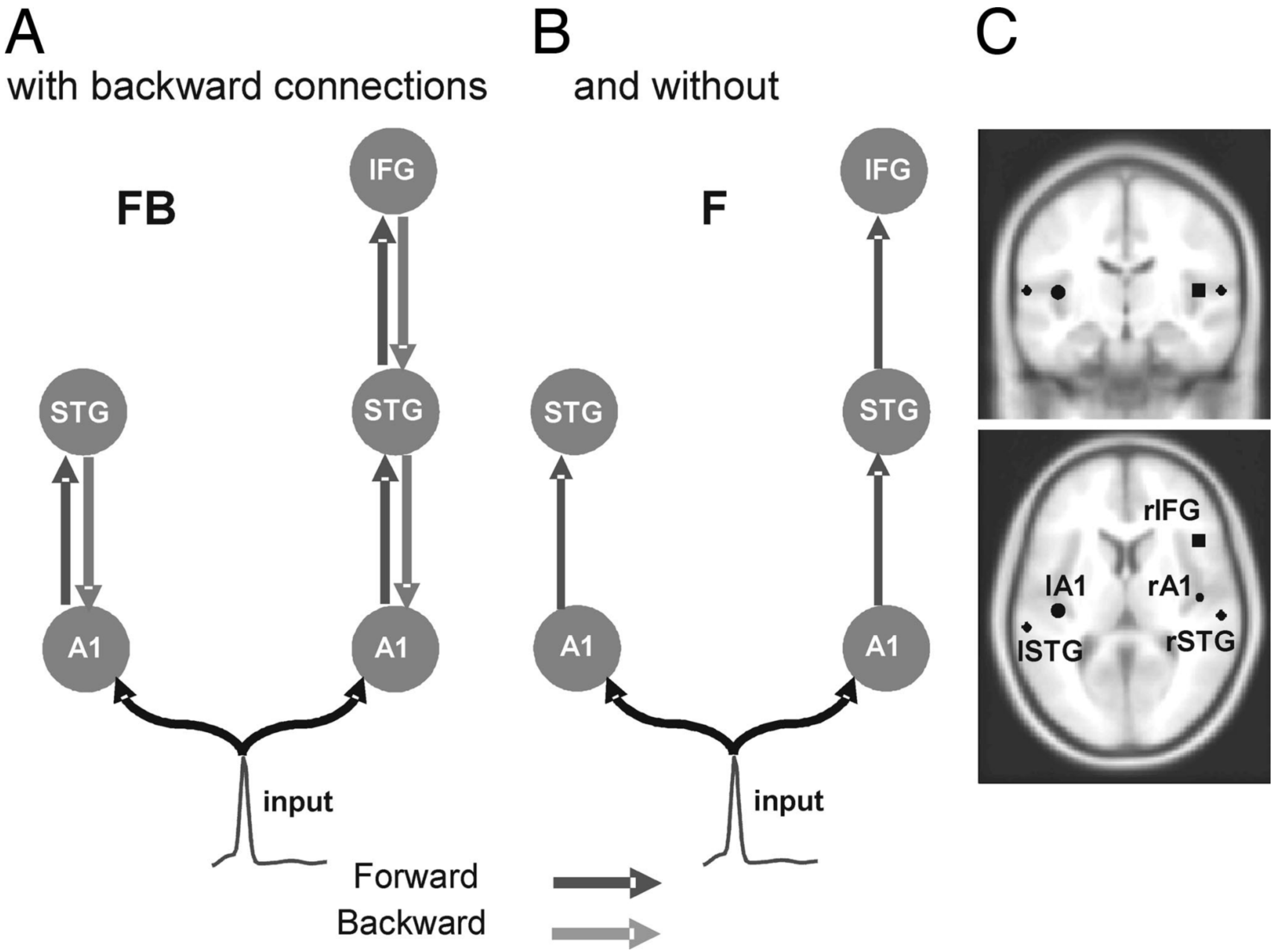
Minimum Norm

Dynamic Causal Modelling



Neural Mass Model

Mismatch negativity (MMN)



Garrido et al., PNAS, 2008

Summary

- Neural activity

  Primary dipole currents reflect postsynaptic potentials in cortical pyramidal cells. Due to ensemble coding and spatial orientation. These induce volume currents to which EEG is sensitive. MEG sensitive to primary and volume currents.

- Forward models

  Spherical model is computationally simpler but ignores eg. anisotropy of conductivity. More appropriate for MEG than EEG. More realistic head models from BEM and FEM methods. MEG not sensitive to radial dipoles.

- Source reconstruction

  ECD methods have few parameters but are nonlinear. Better for early ERP components. Distributed solutions are linear but due to large number of parameters require additional constraints. These constraints can be compared using Bayesian methods. Latest methods explicitly model neural activity.

References

Baillet, S.; Mosher, J.C.; Leahy, R.M.; Electromagnetic brain mapping, Signal Processing Magazine, IEEE Volume 18, Issue 6, Nov. 2001 Page(s):14 – 30.

http://www.scholarpedia.org/article/Volume_conduction

http://www.mrc-cbu.cam.ac.uk/research/eeg/eeg_intro.html

http://www.fil.ion.ucl.ac.uk/spm/doc/biblio/Keyword/MEG.html

Phillips, C et al. An empirical Bayesian solution to the source reconstruction problem in EEG. Neuroimage, 24:997-1011, 2005.

O. David, S.J. Kiebel, L. Harrison, J. Mattout, J. Kilner, and K.J. Friston. **Dynamic Causal Modelling of Evoked Responses in EEG and MEG**. *NeuroImage*, 30:1255-1272, 2006.