Forward and Inverse EEG Source Modeling

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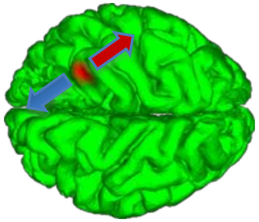
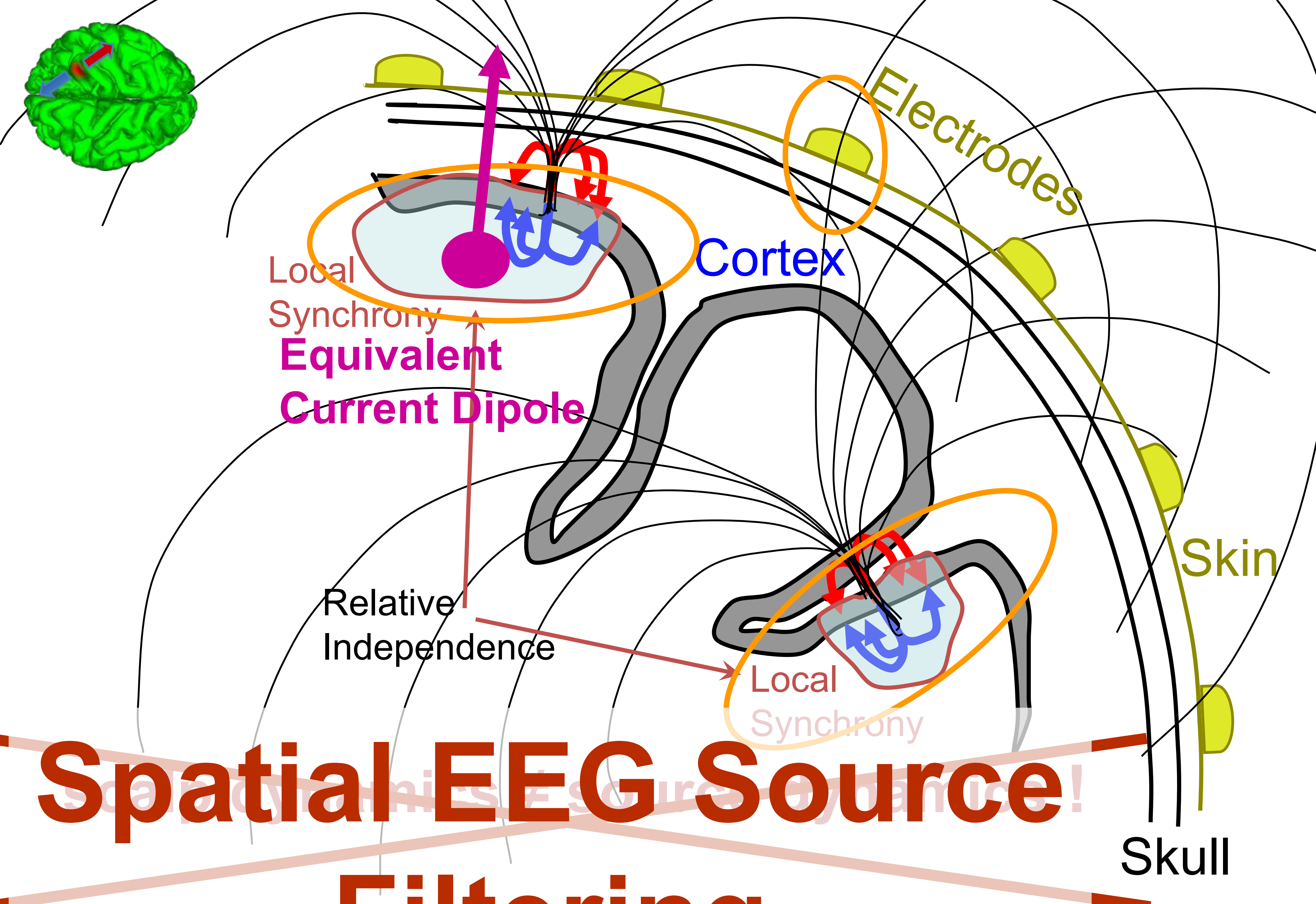


Motivation

- Why perform ICA?
- Why fit dipoles or distribution source models?
- Why measure EEG?!

- To obtain information about brain processes…
  - Time course of activities that produce the EEG signals
  - Locations of the activities that produce the EEG signals

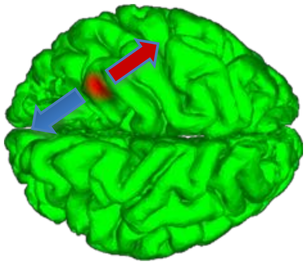
Spatial EEG Source Filtering



S. Makeig 2007

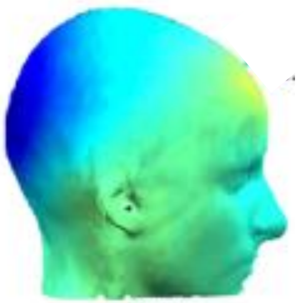
EEG source modeling

Source Space



electrical currents

Sensor Space



recorded potentials

Forward head model

forward problem

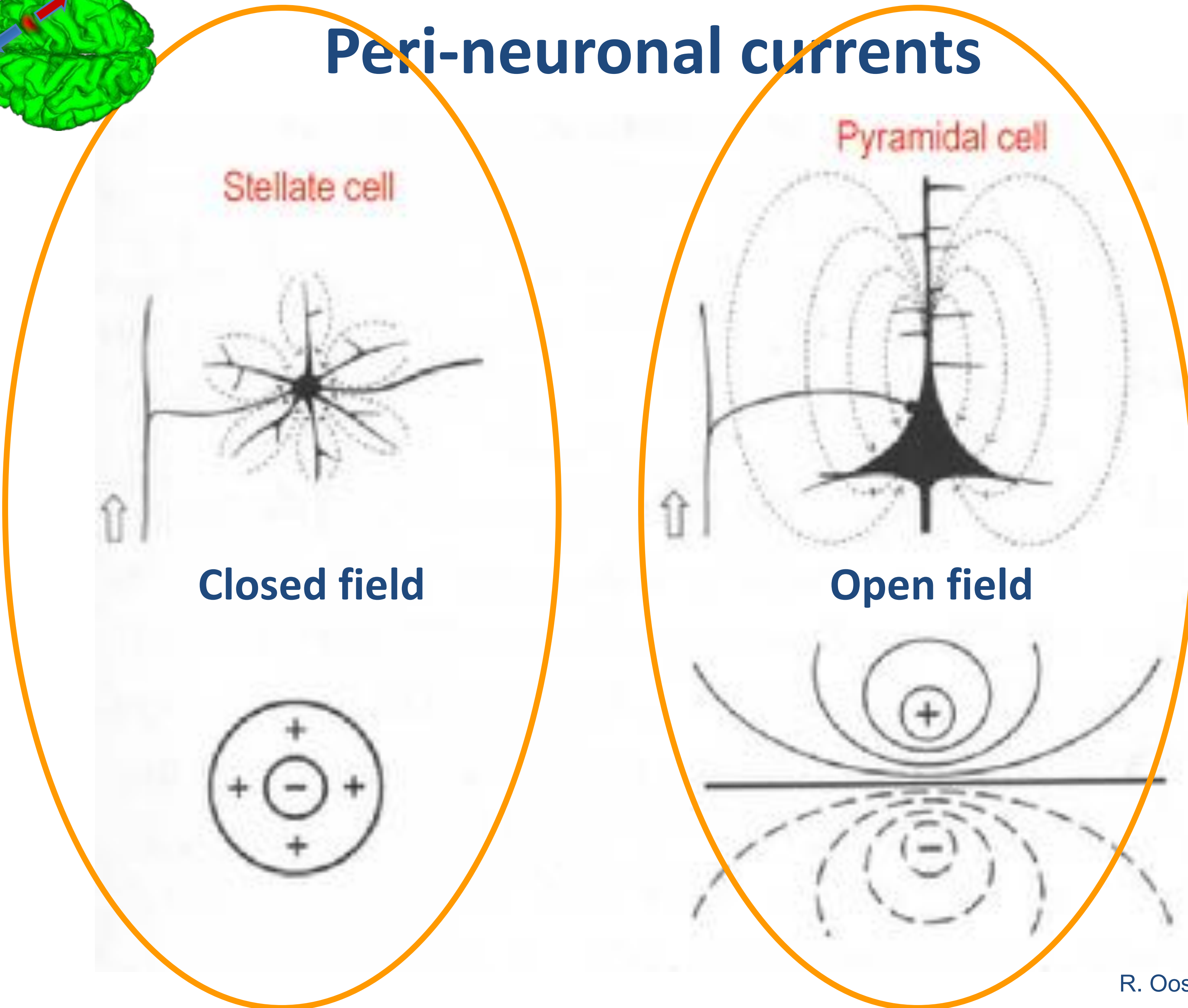
volume conduction through body tissues

inverse problem

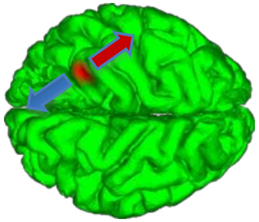
Inverse localization method

R. Oostenveld, & S. Makeig, 2016

Peri-neuronal currents



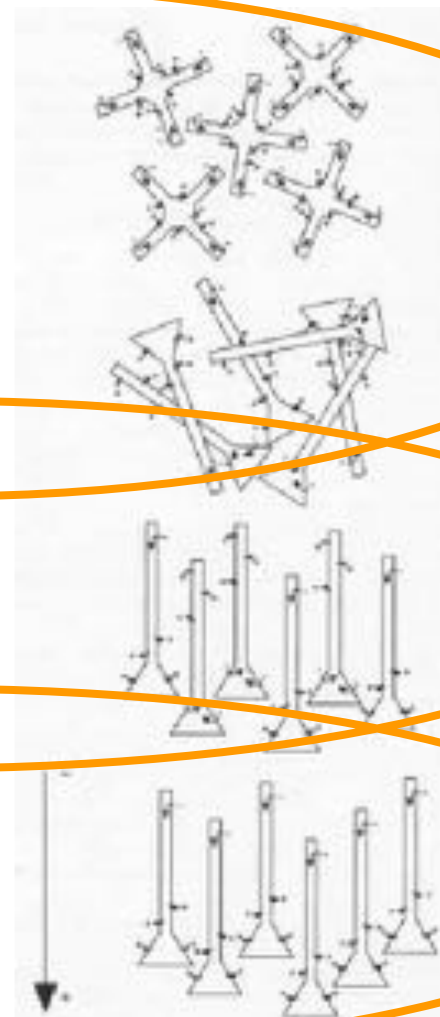
R. Oostenveld, 2007



Symmetry, orientation and activation

radially symmetric, i.e.

randomly-oriented



Closed field

asynchronously activated

Phase cancellation

synchronously activated

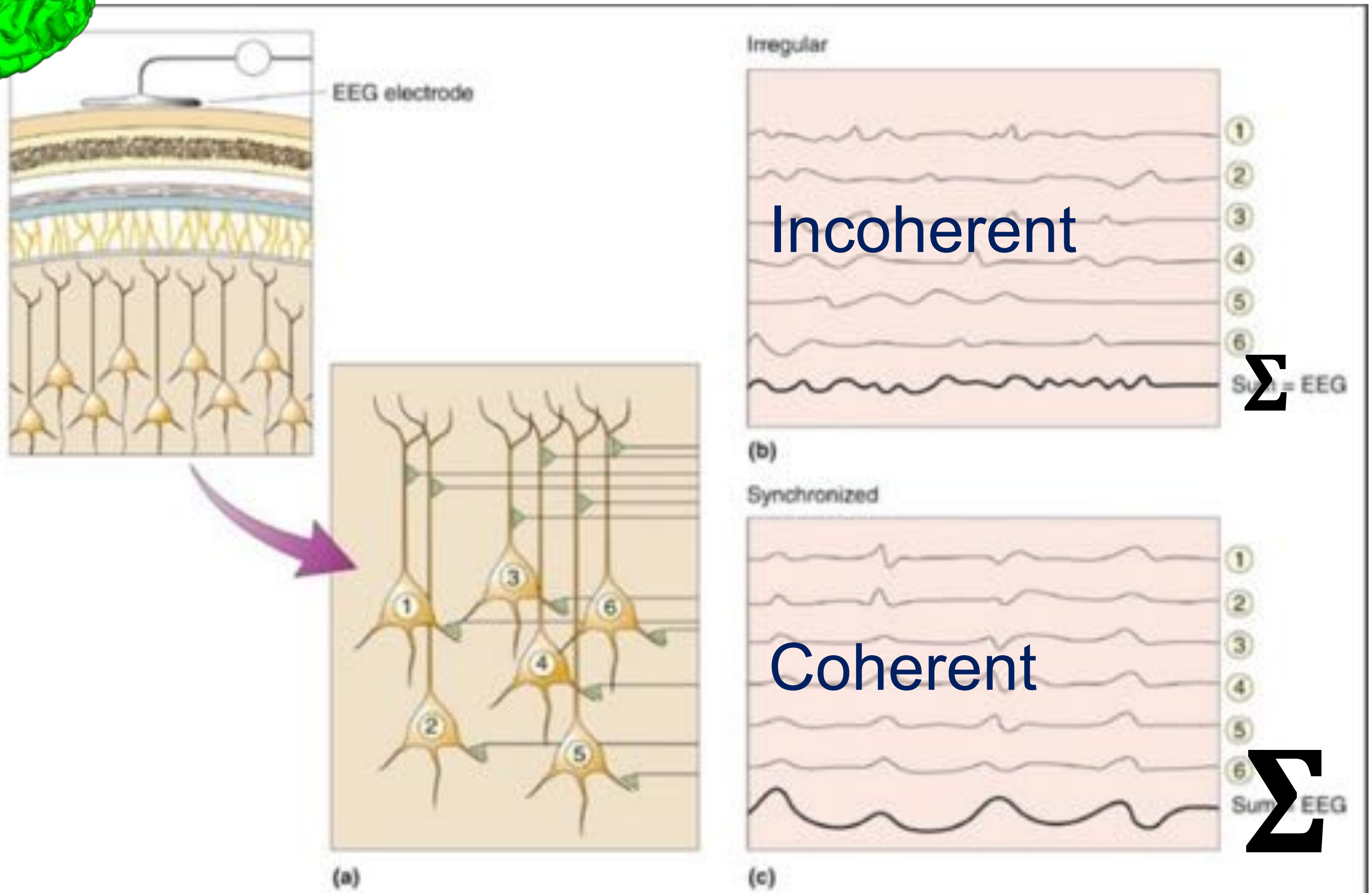
parallel-oriented

Open field

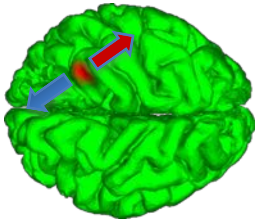
Awhen recorded at a distance, dipolar field components dominate

R. Oostenveld, 2007

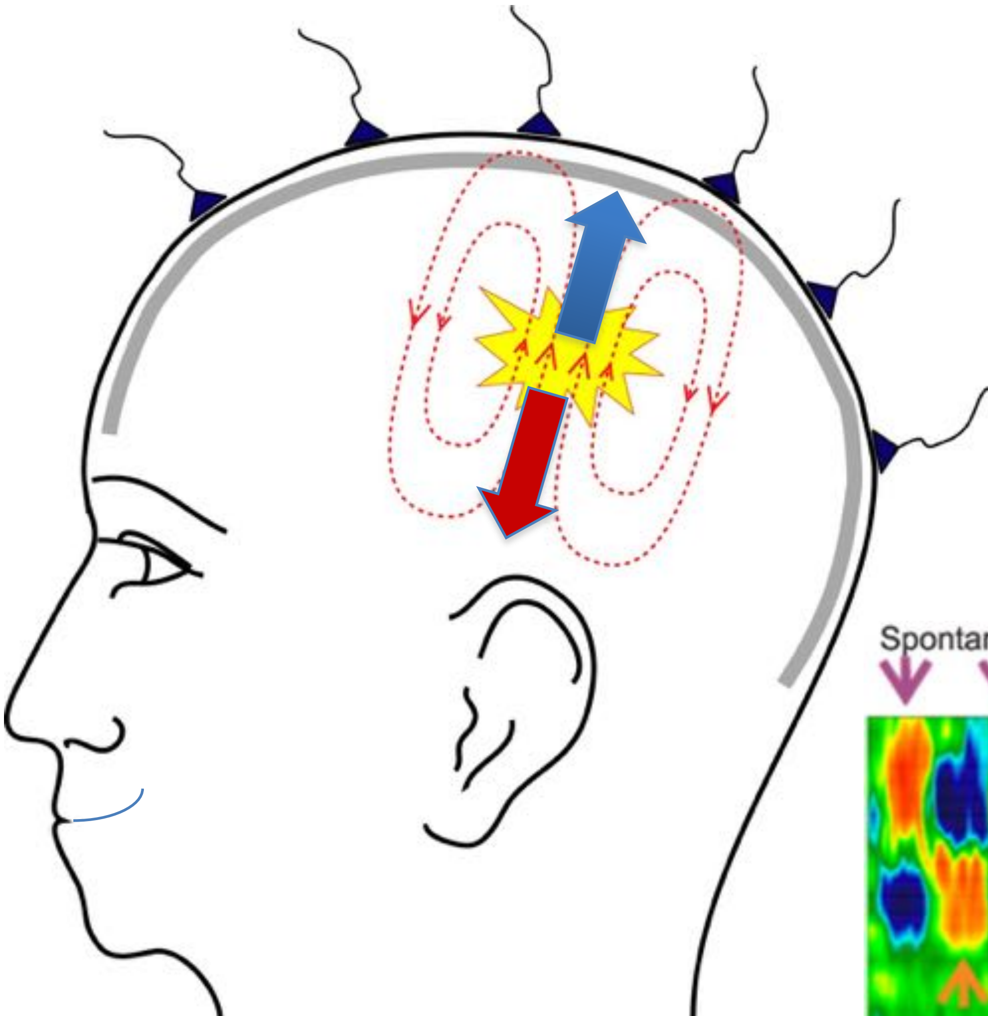
EEG Effective Sources

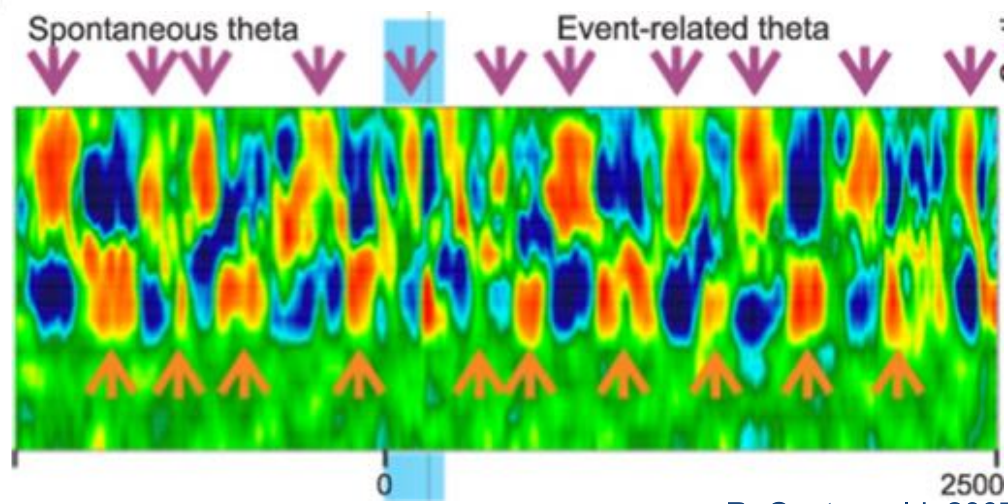


Many neurons need to sum their local field activities to be detectable at EEG electrodes. Synchronized neural activity produces large far field signals.



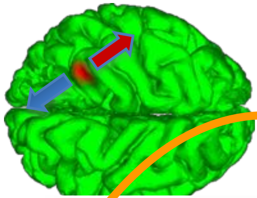
EEG volume conduction of dipolar field patterns ➔ effective sources

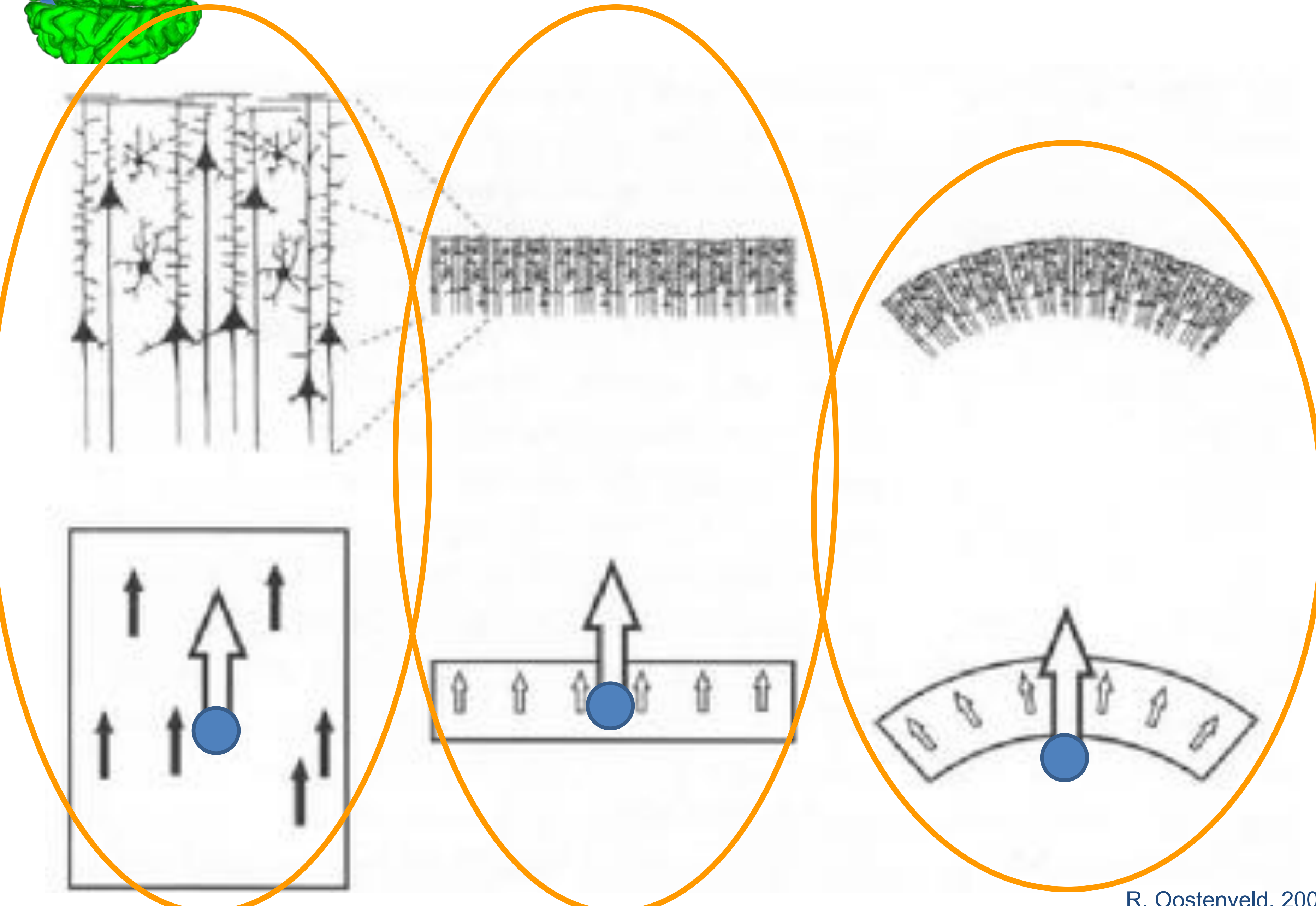




R. Oostenveld, 2007

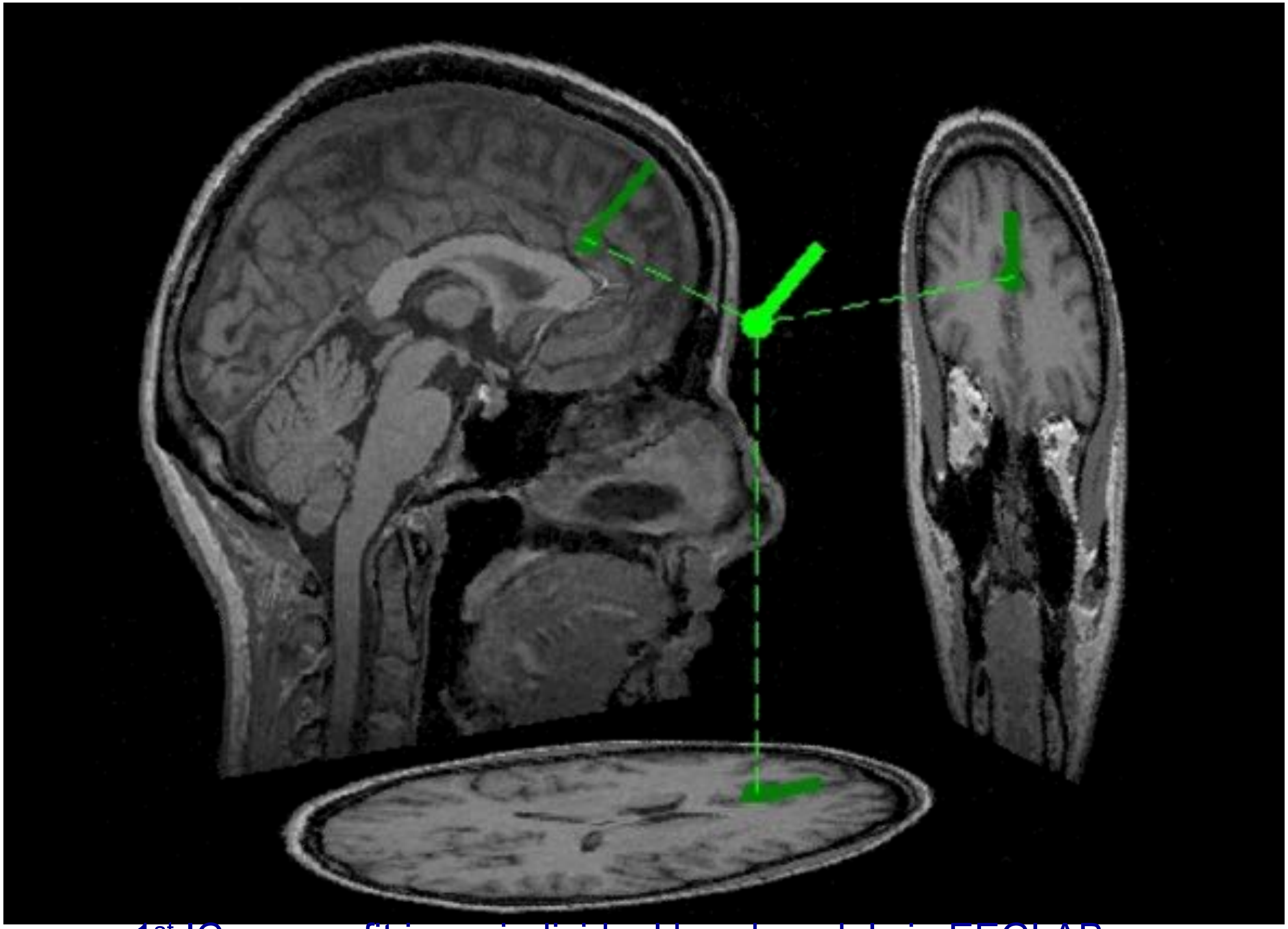
The *equivalent* current dipole





R. Oostenveld, 2007

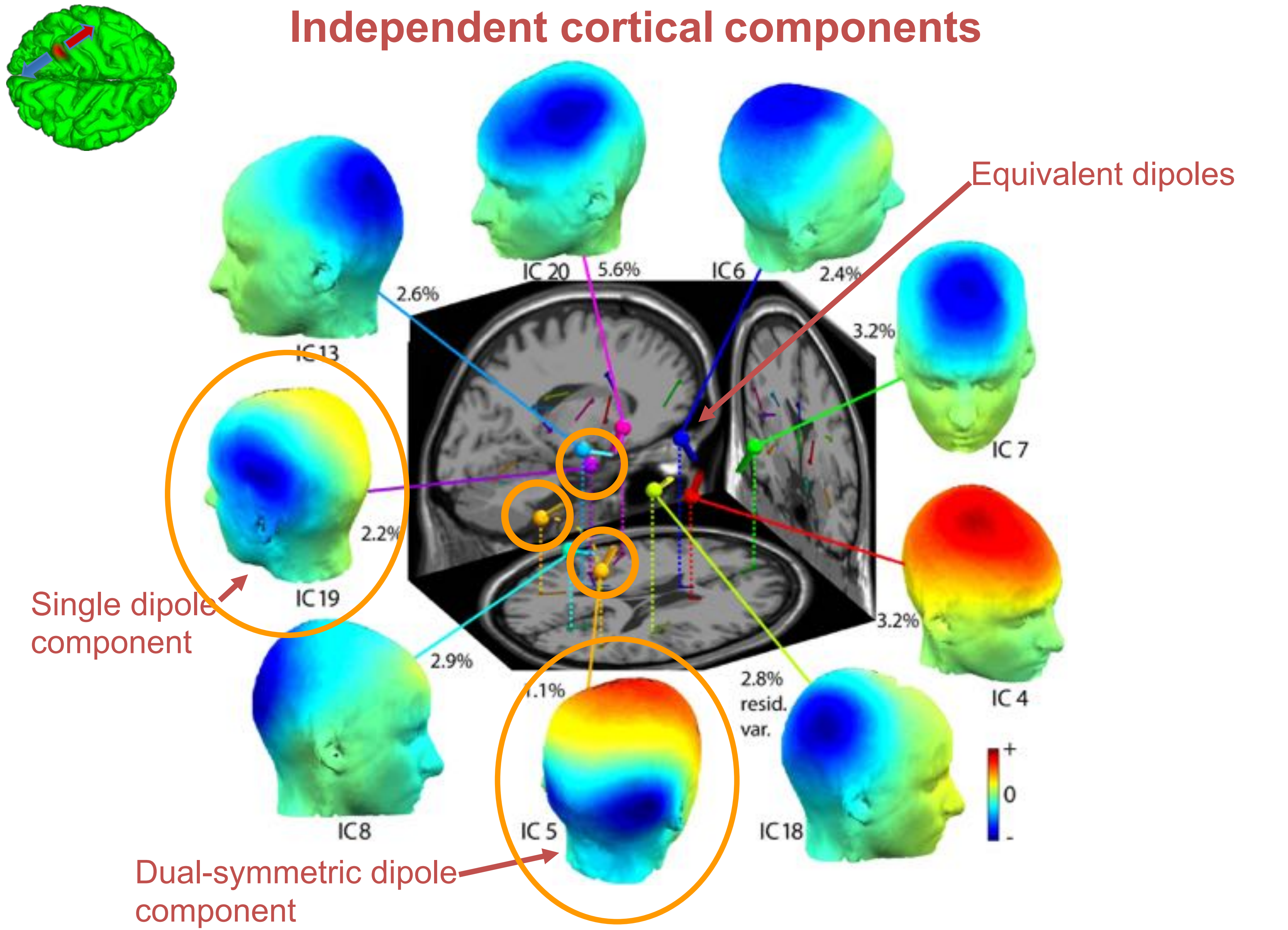
Equivalent current dipole modeling



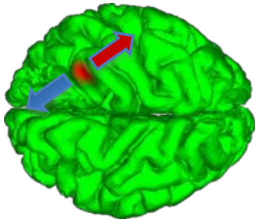
1st IC source fit in an individual head model via EEGLAB

A. Delorme, ~2007

Independent cortical components

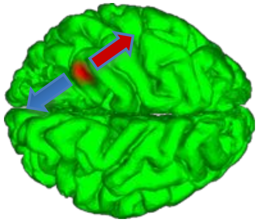


Julie Onton & S. Makeig (2006)

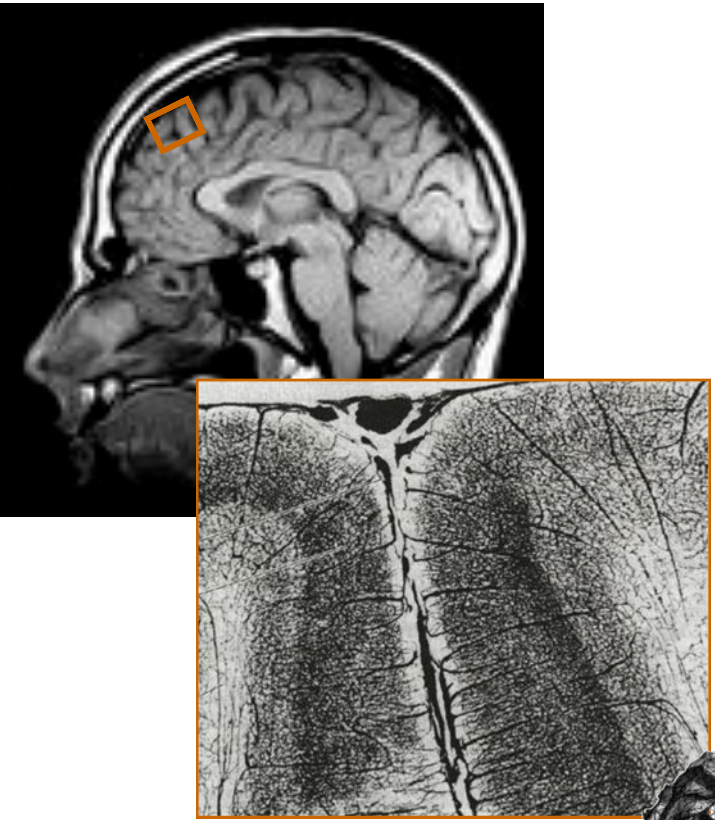


Equivalent current dipole modeling

- **Physical/mathematical motivation**
  - Any current distribution can be written as a multipole expansion
  - First term: monopole (must be 0)
  - Second term: dipole
  - Higher order terms: quadrupole, octopole, …
  - **In far-field recordings, the dipolar term dominates.**
- For convenience + accuracy, therefore
  - **Dipoles** can be used as building blocks in distributed EEG effective source models

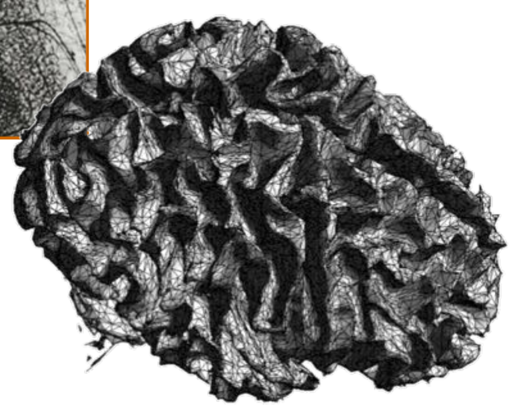


The linear forward problem



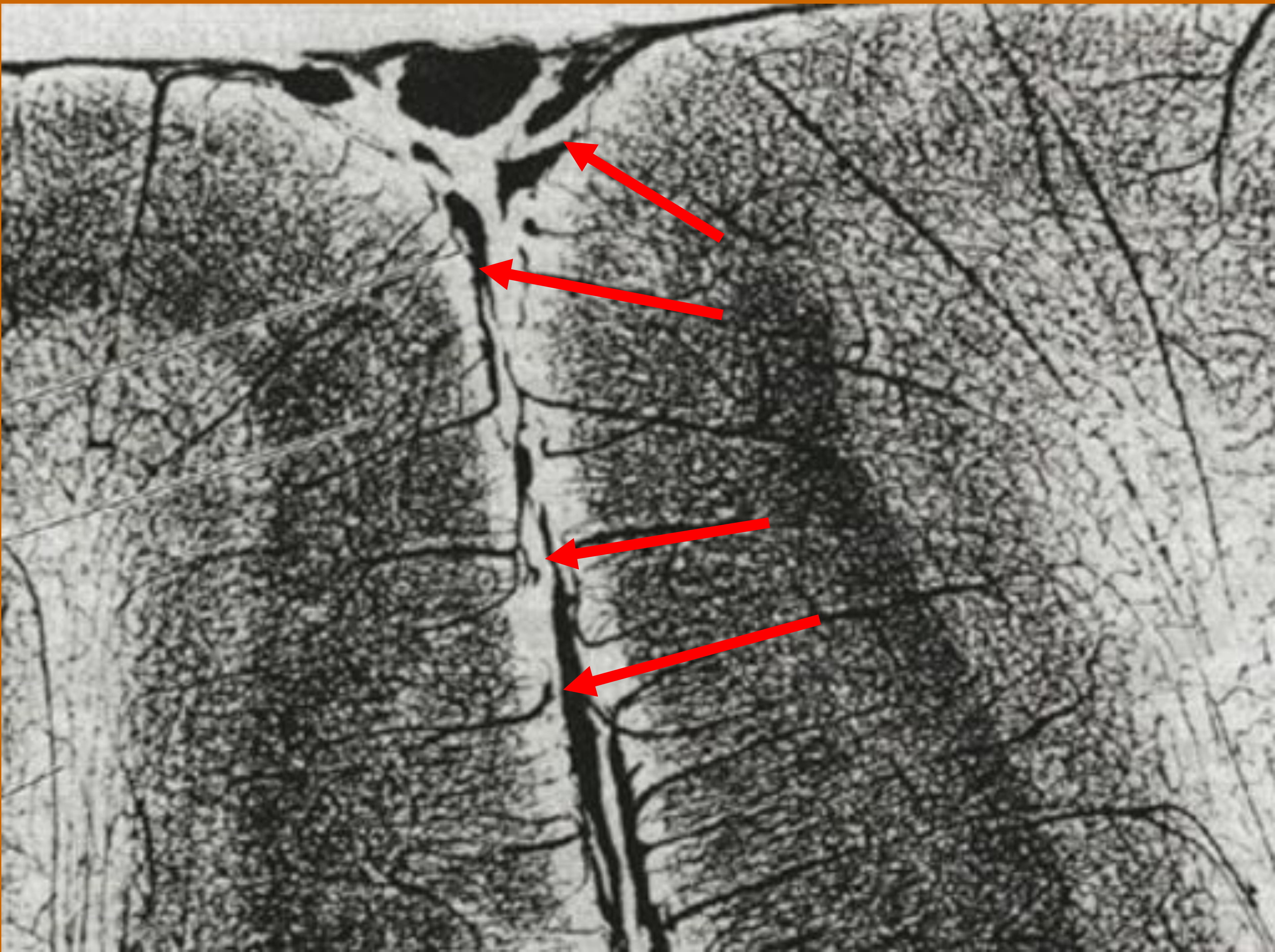
$$X = LS$$

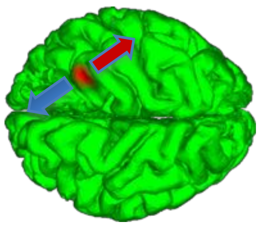
where ***L*** is the lead field matrix giving Potential vector contributions ***X*** to each scalp electrode for all possible source contributions ***S*** (source space)



Daunizeau, 2009

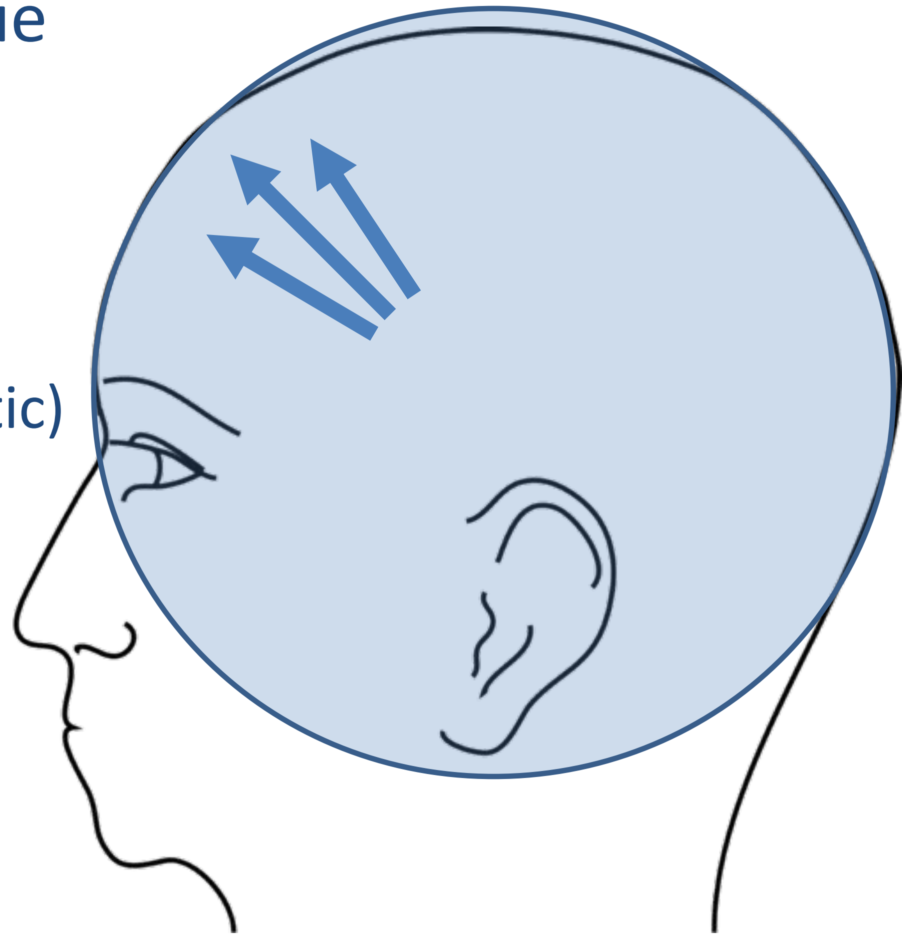
Anatomical constraint:
Sources are in the cortex & perpendicular to it.





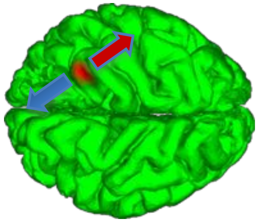
Forward Head Models

- Electrical properties of tissue
  - Conductivity
  - Anisotropy
- Geometrical description
  - Spherical model? (less realistic)
  - Realistically shaped model



→ A **forward model** describes
how the currents flow
from all possible points of origin

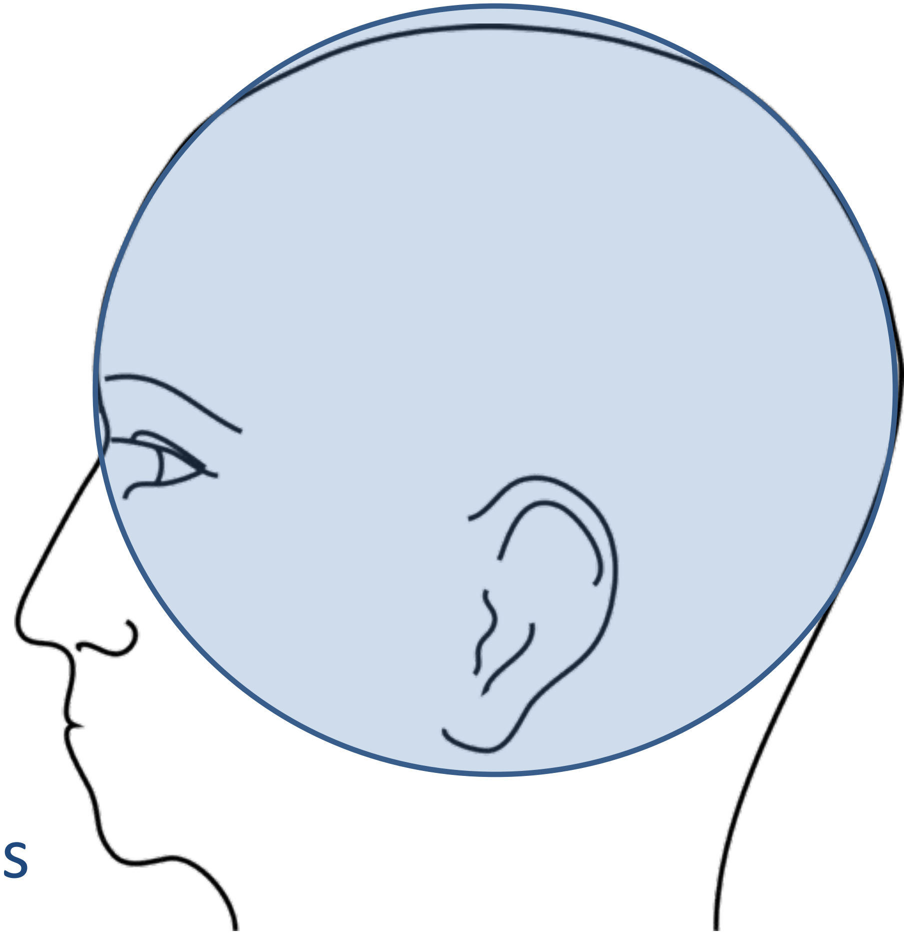
R. Oostenveld, & S. Makeig, 2016



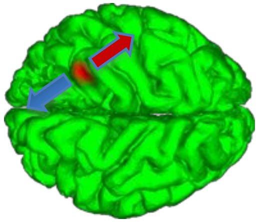
Forward Head Models

- Advantages of the **spherical** model
  - mathematically accurate
  - reasonably accurate
  - computationally fast
  - easy to use

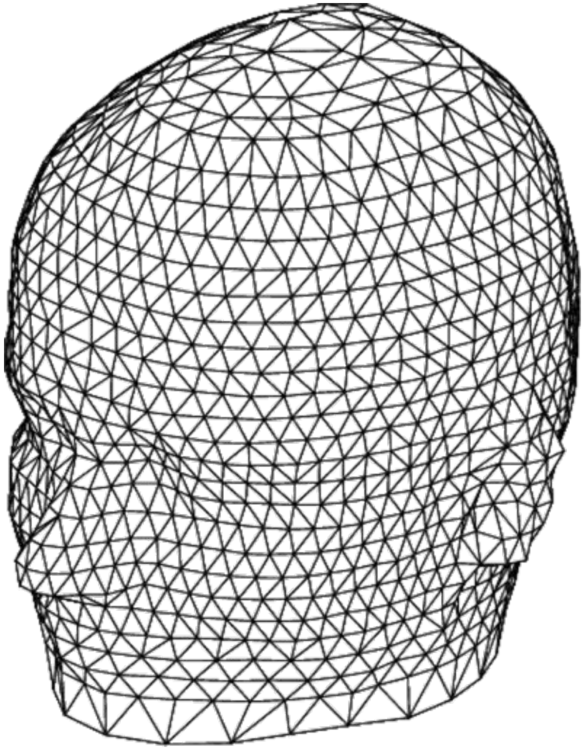
- Disadvantages of the **spherical** model
  - inaccurate in some regions
  - difficult to align to head



R. Oostenveld, & S. Makeig, 2016



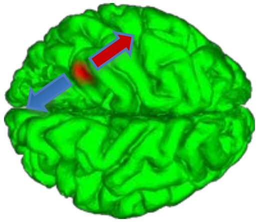
Forward Head Models



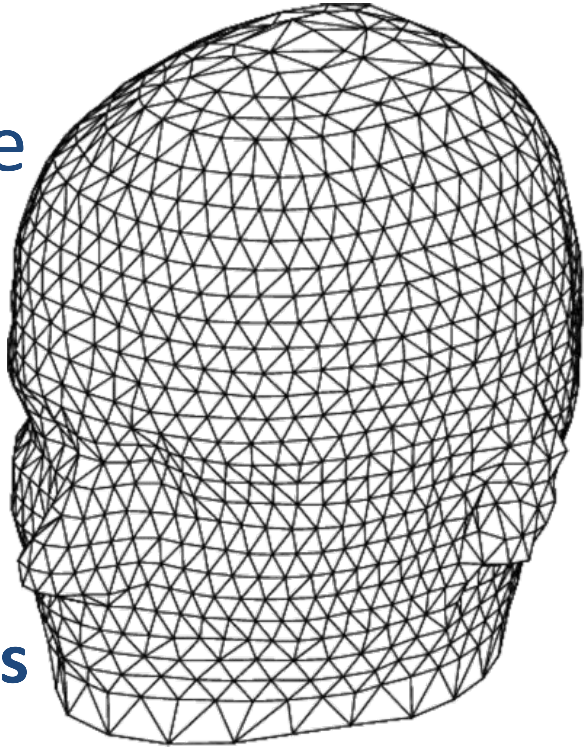
- Advantages of a **realistic** head model
  – accurate solution for EEG
- Disadvantages of a **realistic** model
  – more work
  – computationally slower
  – numerically instable?
  – More difficult inter-individual comparisons

→ The pragmatic (easy, cheap) solution is to use a standard (mean) realistic head model (MNI).

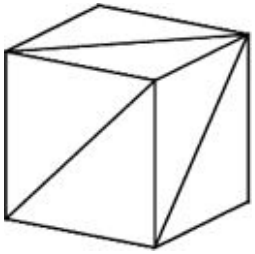
R. Oostenveld, & S. Makeig, 2016



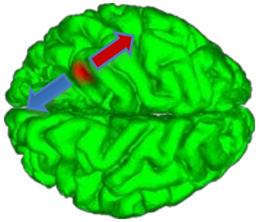
Forward Head Models



- Computational methods for volume conduction problem that allow realistic geometries
  - **Boundary Element Method (BEM) models**
  - **Finite Element Method (FEM) models**
- Geometrical description
  - **Triangles** (2-D) → BEM
  - **Tetrahedra** (3-D) → FEM



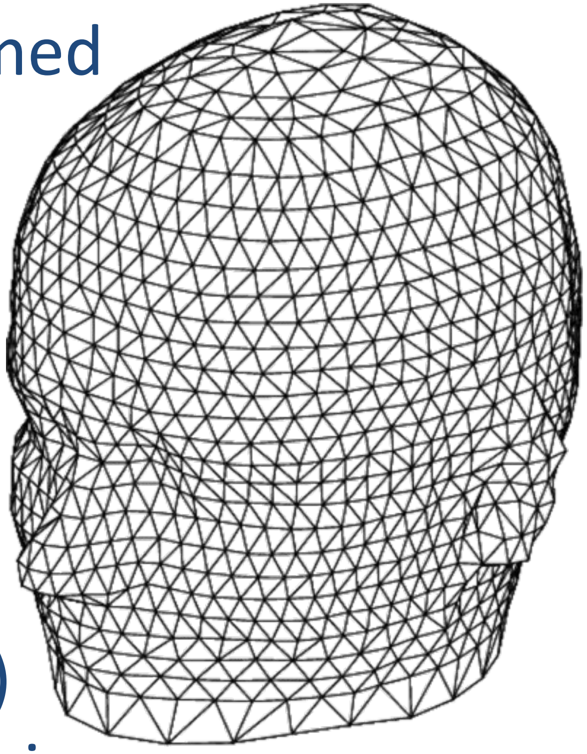
R. Oostenveld, & S. Makeig, 2016



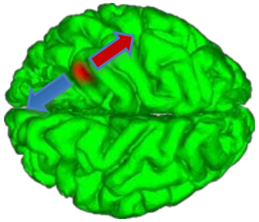
Forward Head Models: BEM

- **Boundary Element Method (BEM)** models
  - description of head geometry by tissue compartments
  - Tissue in each compartment is assumed
    - homogenous
    - isotropic

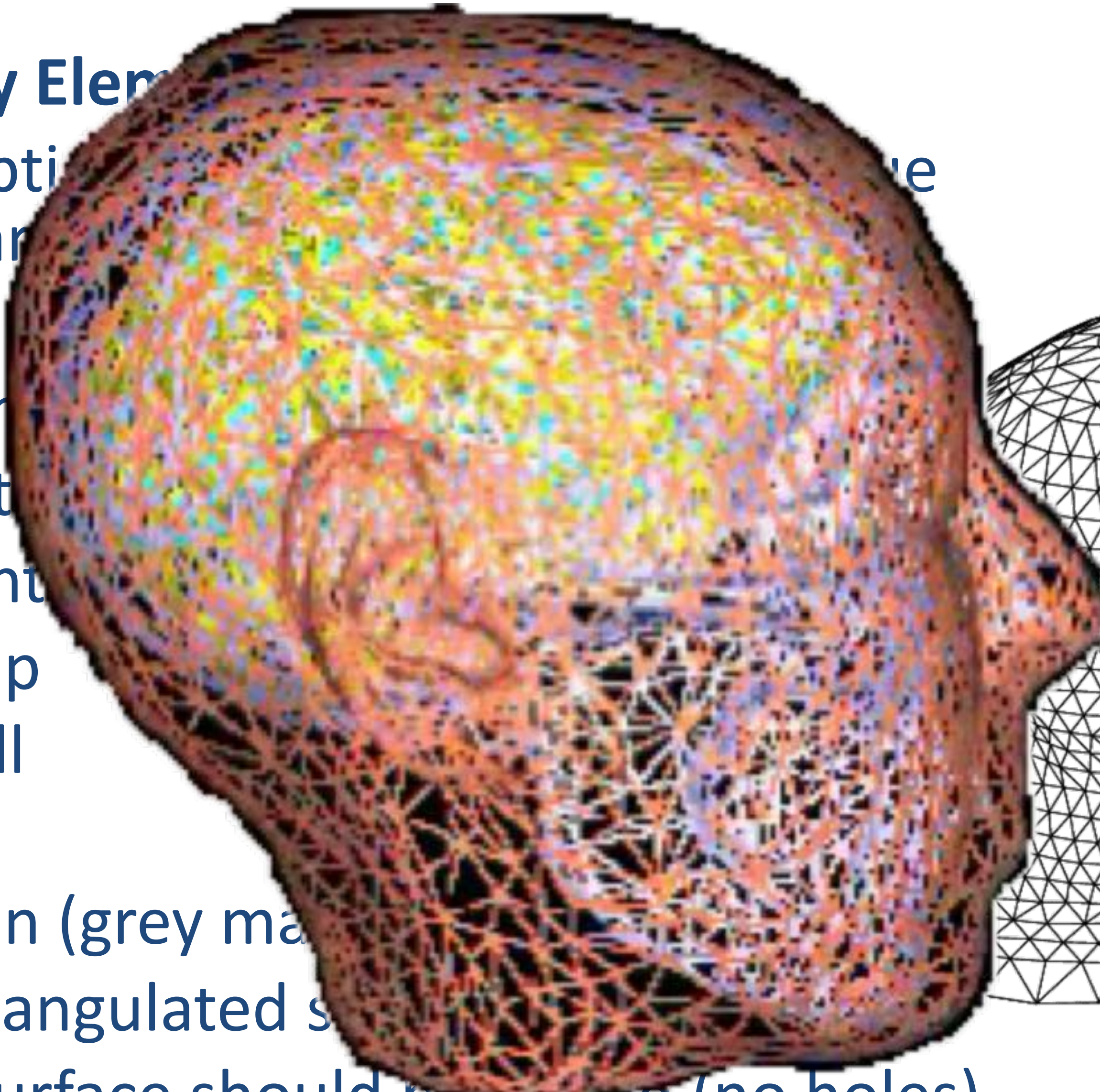
  Important tissue types
    - Scalp
    - Skull
    - CSF
    - Brain (grey matter / white matter)
  - Use triangulated surfaces as boundaries
  - Each surface should be closed (no holes)

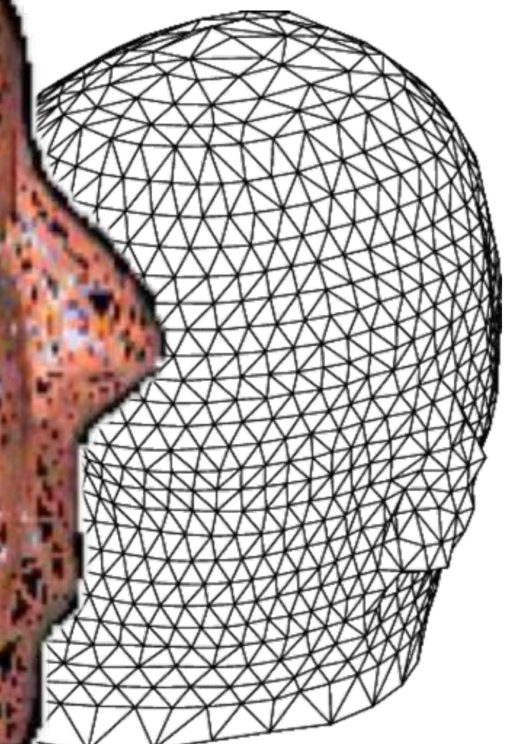


R. Oostenveld, & S. Makeig, 2016



Forward Head Models: BEM





- **Boundary Elem**
  - descripti e
    compar
  - Tissue
    - hom
    - isot

  Important
    - Scalp
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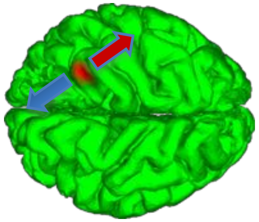
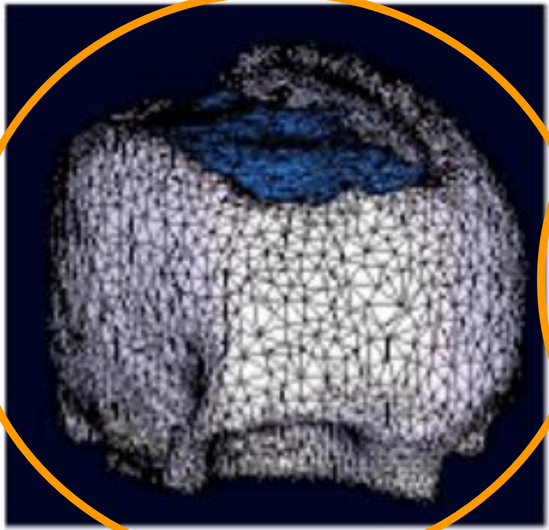
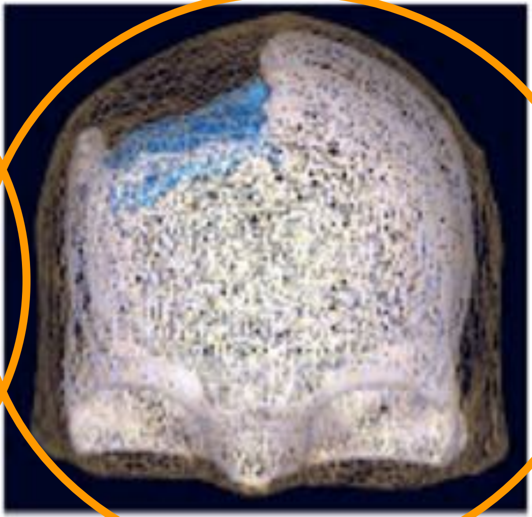
R. Oostenveld, & S. Makeig, 2016



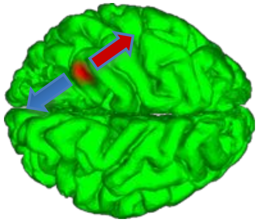
Mapping sources of intracranial data recorded to plan brain surgery





Non-conductive 'plastic layer' (the ECoG electrode sheet and strip)

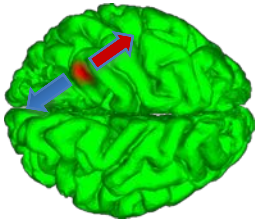
Zeynep Akalin Acar,, S. Makeig, G. Worrell, '09-'16



Forward head models: Modeling the skull

- **EEG = 'Potential differences between electrodes,'** a measure of summed current flowing through scalp.
  - However, only a tiny fraction of *brain source currents* pass through the skull.
  - Therefore a forward head model should describe *brain, skull,* and *scalp tissues* as accurately as possible.
  - Skull is the most resistive, therefore knowing its conductance most important.

R. Oostenveld, & S. Makeig, 2016



Forward head models: Modeling the skull

- **Problems with skull modeling:**
  – Poorly visible in an anatomic MRI (T2) image
  – Thickness varies regionally
  – Conductivity is not homogeneous (isotropic?)
  – Complex geometry at front and base of skull

→ **Skull conductivity** varies across individuals and has no direct measurement method.

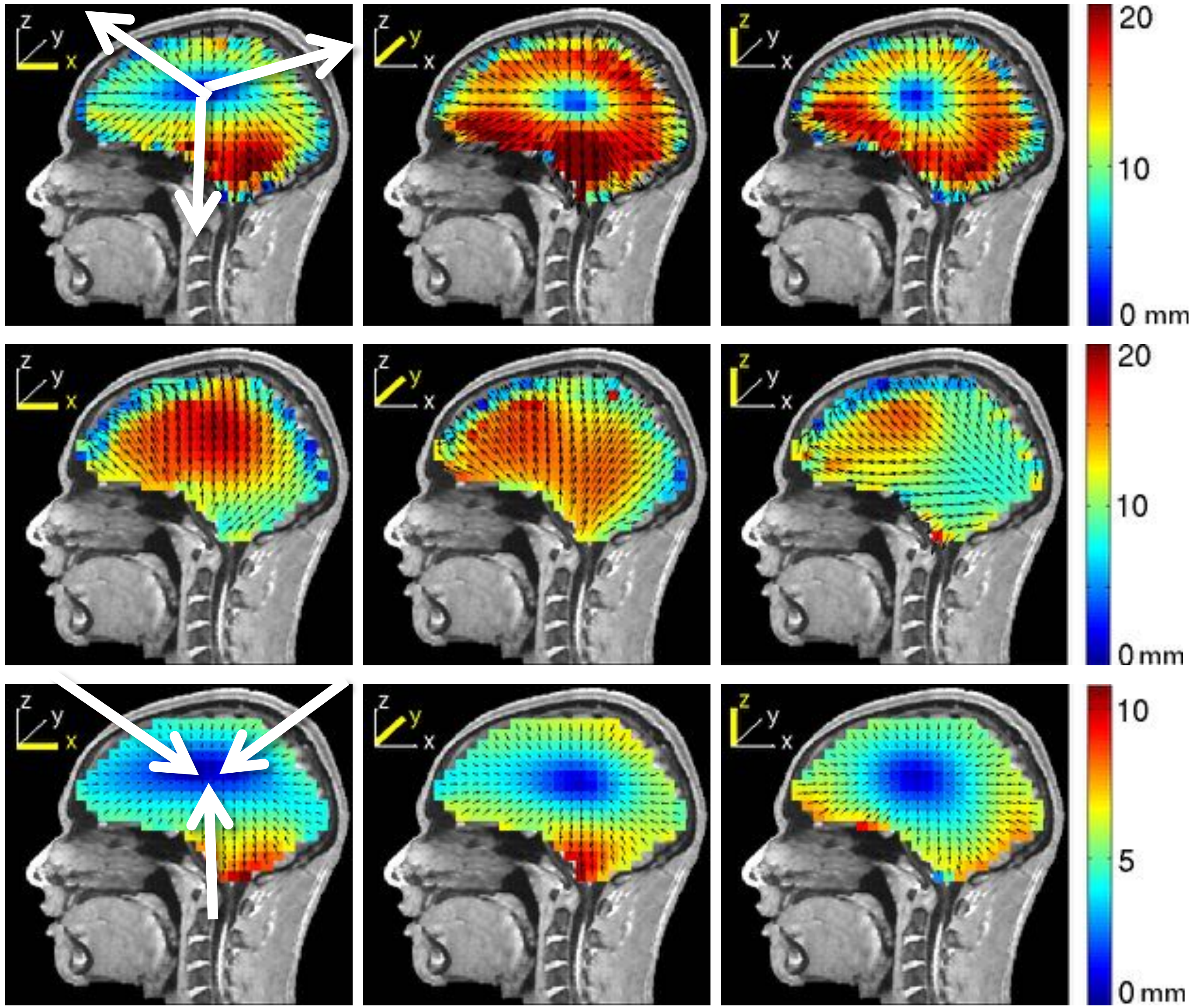
R. Oostenveld, & S. Makeig, 2016

Effects of Mis-Estimating Skull Conductivity

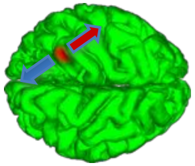
BSCR
Simulate 25
↑ RLS_{25}-4
↓ RLS_{80}-4
Assume 80

Simulate 25
↑ RLS_{25}-4
↓ wMNI_{80}-4
Assume 80
Template head

Simulate 25
↑ RLS_{25}-4
↓ RLS_{15}-4
Assume 15



Akalin Acar & Makeig, 2013

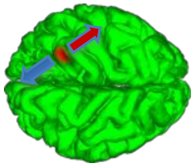


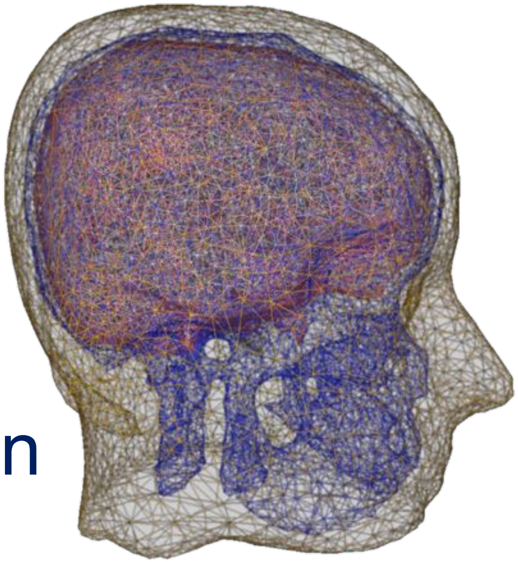
The FEM volume conductor model

To make a Finite Element Method (FEM) head model:

- **Tesselate the 3-D volume into solid tetrahedra**
  - Contains a large number of 3-D elements
  - Each tetrahedron can have its own conductivity
  - Each tetrahedron can have its own ***anisotropy*** (direction-dependent conductivity differences)
- **FEM is the more complete numerical method** (> BEM)
  - But is computationally expensive
  - Note: Accurate conductivities are not known, particularly for skull (and scalp?).

R. Oostenveld, & S. Makeig, 2016





- **Head Modeling Errors**

  Electrode & MR image co-registration

  Head geometry errors

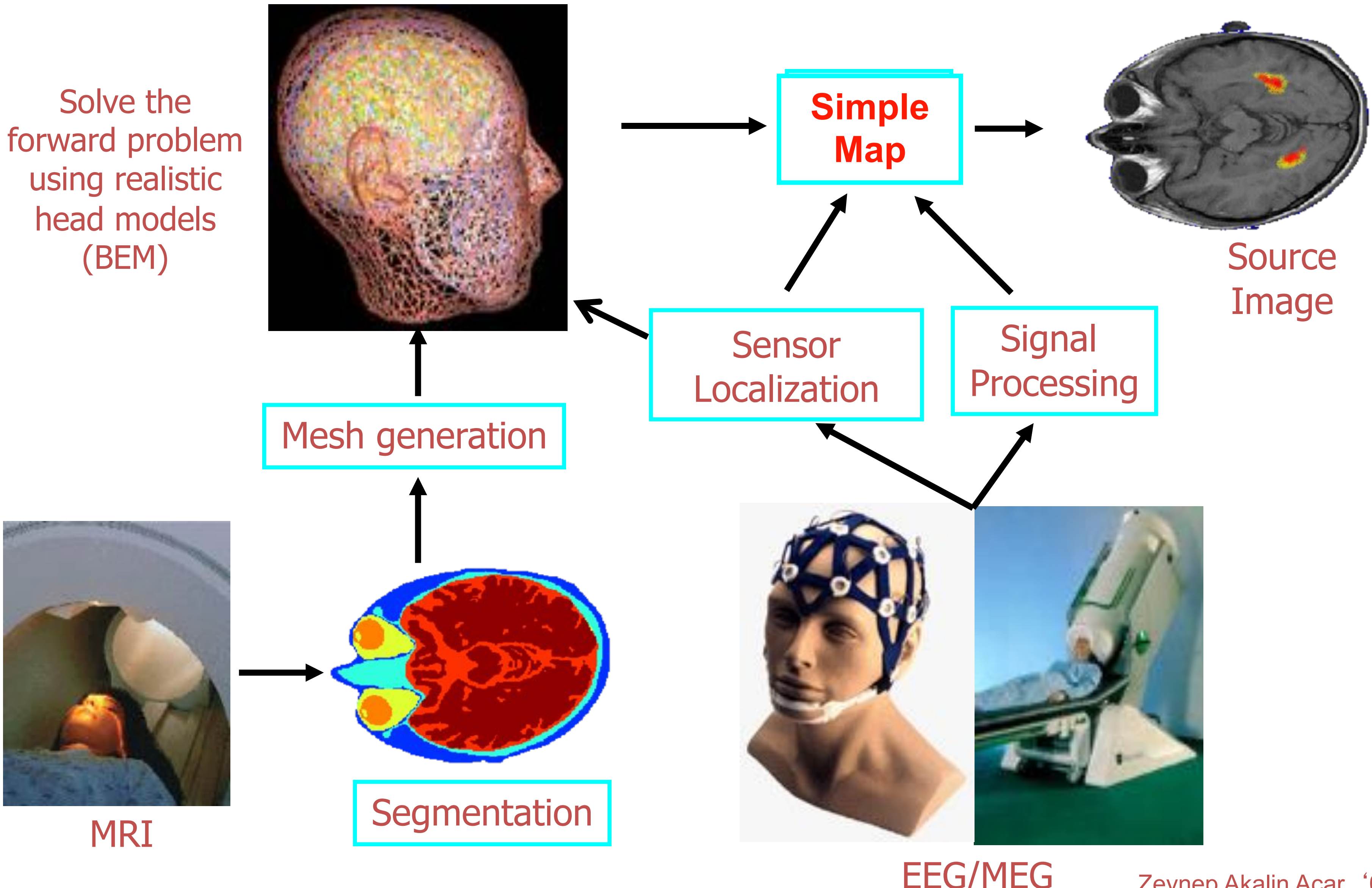
  EXCLUSION of white matter

  Two few electrodes

  Poor distribution of electrodes

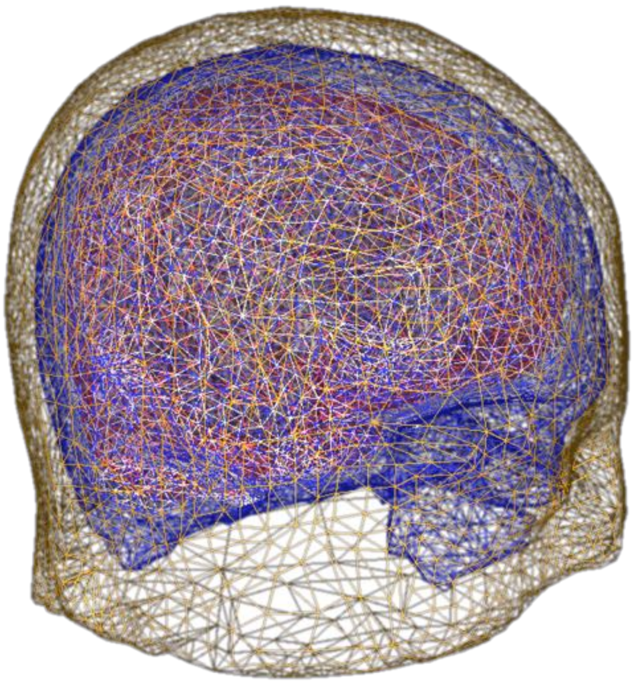
  Mis-estimation of skull conductivity!

Electromagnetic source localization using realistic head models (Dipfit, NFT)

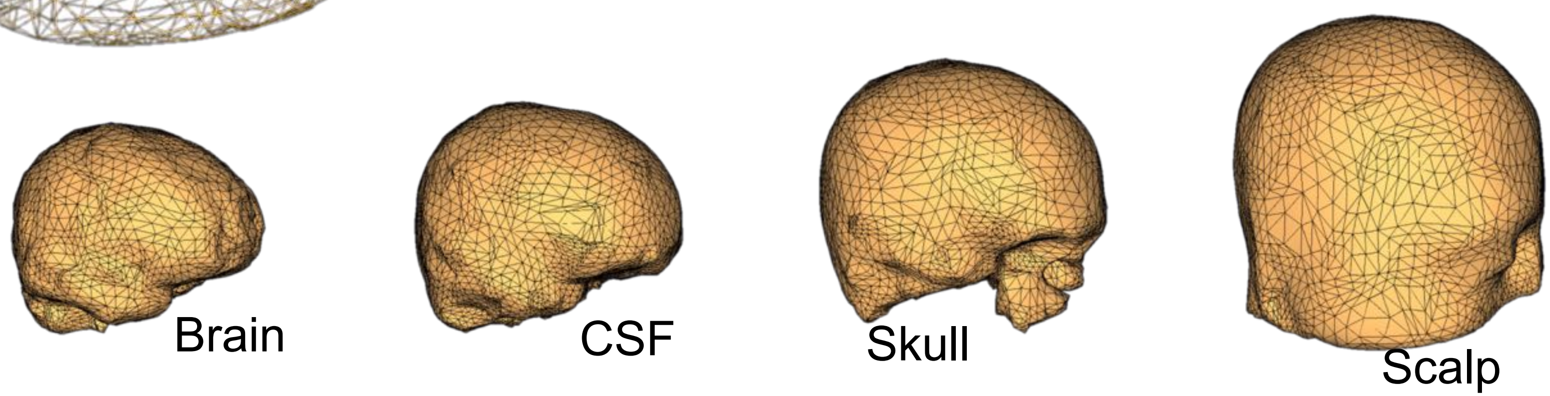


Zeynep Akalin Acar, ‘06

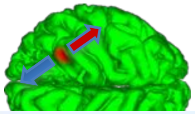
The MNI Head Model

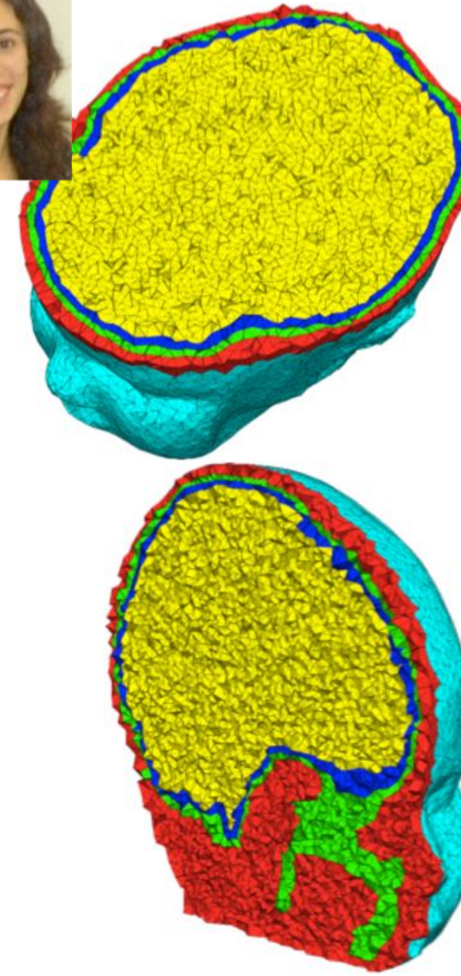


- 4-layer
  - 16856 nodes
  - 33696 elements
- 3-layer
  - 12730 nodes
  - 25448 elements



NFT



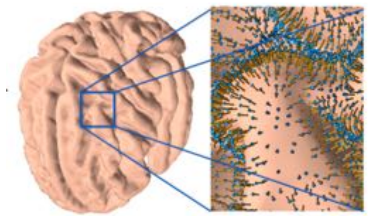


FEM models

BEM models

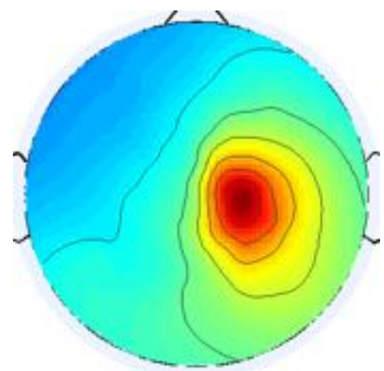
Akalin Acar & Makeig, 2010

NIST

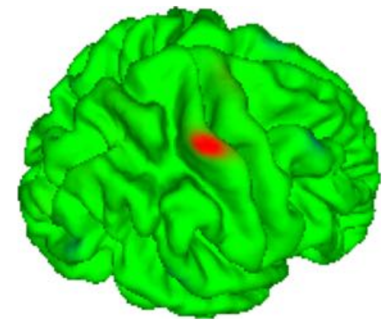


Source space

Scalp map



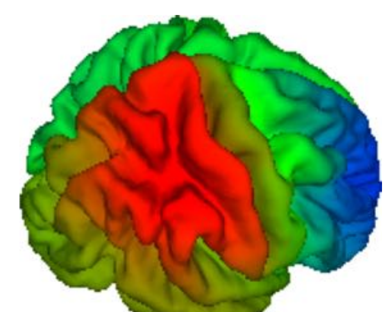
SCS



Cheng Cao, 2012

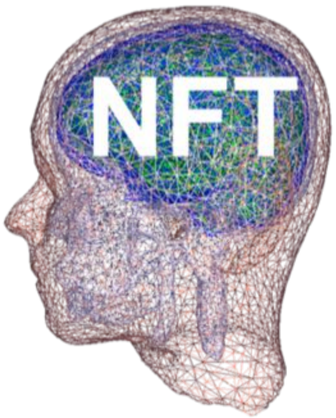
Patch-based SBL

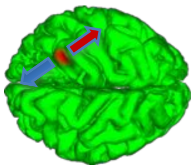
sLORETA



Head Model Generation Summary

- **Subject-specific Head Model (NFT)**
  - From whole head T1 weighted MR of the subject
  - 4-layer realistic BEM model
- **MNI Template Head model (DIPFIT)**
  - From the MNI head
  - 3-layer and 4-layer template BEM model
- **Warped MNI Template Head Model (NFT)**
  - Warp MNI template to EEG sensors
- **Spherical Head model (deprecated)**
  - 3-layer concentric spheres
  - Fitted to EEG sensor locations
  - Not accurate

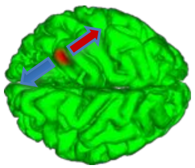




Inverse source localization

- **Single and multiple dipole models**
  - Minimize error between the model and the measured potential/field
- **Distributed dipole models**
  - Seek perfect fit to the measured potential or field
  - Must minimize **some additional source constraint**
    - LORETA assumes a smooth source current distribution
    - Minimum Norm (L2), min. total cortical $|\text{current}|^2$
    - Minimum Current (L1) min. total cortical $|\text{current}|$
    - Note: L2/L1 need some weighting scheme to keep source models from being too broad & superficial.

R. Oostenveld, & S. Makeig, 2016



Inverse methods

Spatial filtering approaches

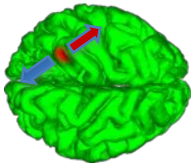
- **Scan whole brain** with single dipole and compute the filter output at every location (using sensor covariance)
  - MUSIC
  - *Beamforming* (e.g., LCMV, SAM, DICS)

- **Perform ICA decomposition** (higher-order statistics) on the *continuous* data.
  - ICA gives the projections of the sources to the scalp surface → '**simple**' **maps**!

→ICA solves 'the first half' of the inverse problem: 'What?'

→ICA gives 'simple' source maps, helping to locate: 'Where?

R. Oostenveld, & S. Makeig, 2016



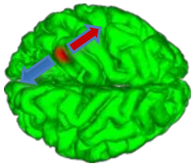
Single or multiple dipole models

- Manipulate source parameters to **minimize error** between measured and model data
  - The **position** of each source
  - The **orientation** of each source
  - The **strength (magnitude)** of each source

- **Dipole orientation** and **strength** together correspond to the "**dipole moment**," estimated linearly
- **Dipole position** is estimated non-linearly by

  source parameter estimation

R. Oostenveld, & S. Makeig, 2016

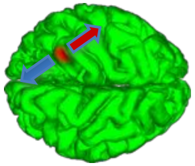


DIPFIT: Dipole fitting 1. Grid search

1. Coarse fit step

- Define a grid with possible dipole locations
- Compute optimal dipole moment at each location
- Compute value of goal-function (fit to given map)
- Plot value of goal-function on the grid → find best fit.
- Number of evaluations:
  - single dipole, 1 cm grid: ~4,000
  - single dipole, ½ cm grid: ~32,000
  - BUT two dipoles, 1 cm grid: ~16,000,000

R. Oostenveld, & S. Makeig, 2016



DIPFIT: Dipole fitting 2. Nonlinear search

2. Fine fit step

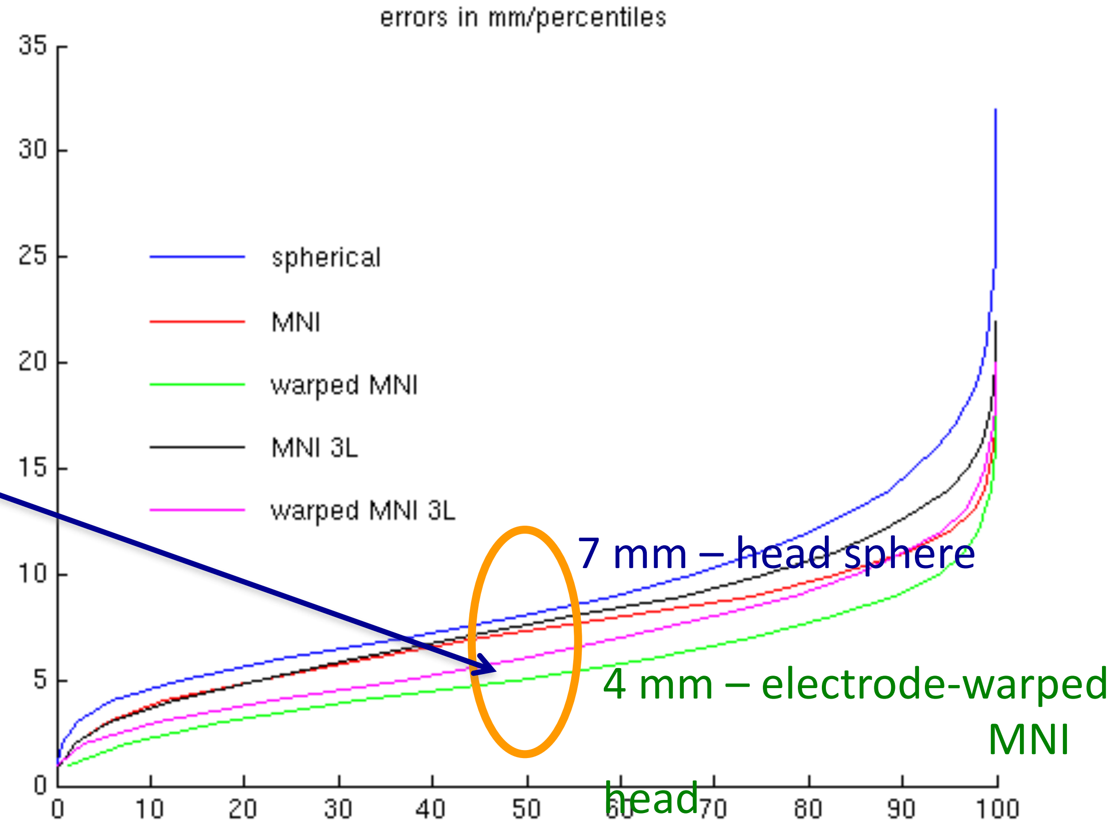
Start with the initial guess from coarse fitting

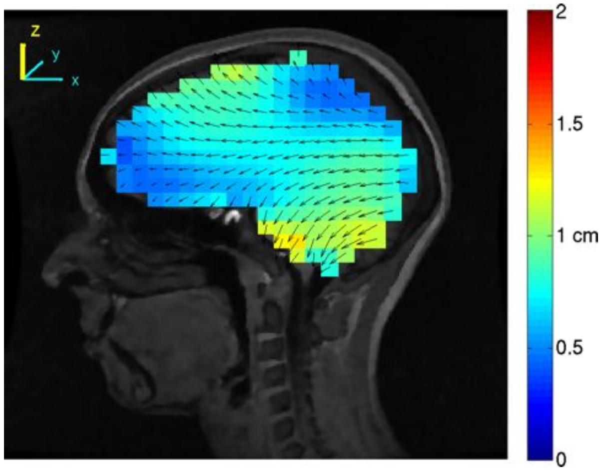
- Evaluate the local derivative of the goal (fit) function
- Then "walk down hill" to the most optimal solution

Number of iterative steps required = ~100

Effect of Template Head Model Choice On Estimated Dipole Locations

By Simulation: The median geometric error in dipole localization using the MNI template head model warped to measured electrode positions is only 4 mm.

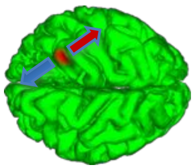




BUT Additional dipole error contributors:

- Electrode co-registration error
- ICA numerical error (not enough data?)
- Source model geometry error
- Conductance value error (skull)

Z. Akalin Acar & S Makeig, 2013



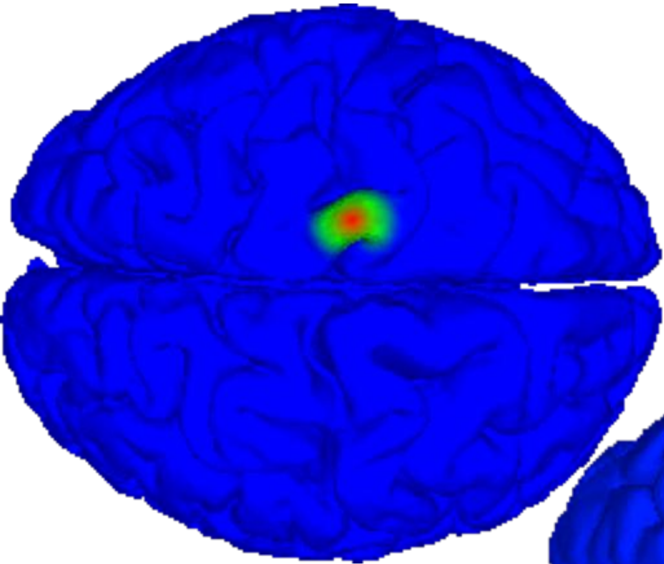
Distributed source models

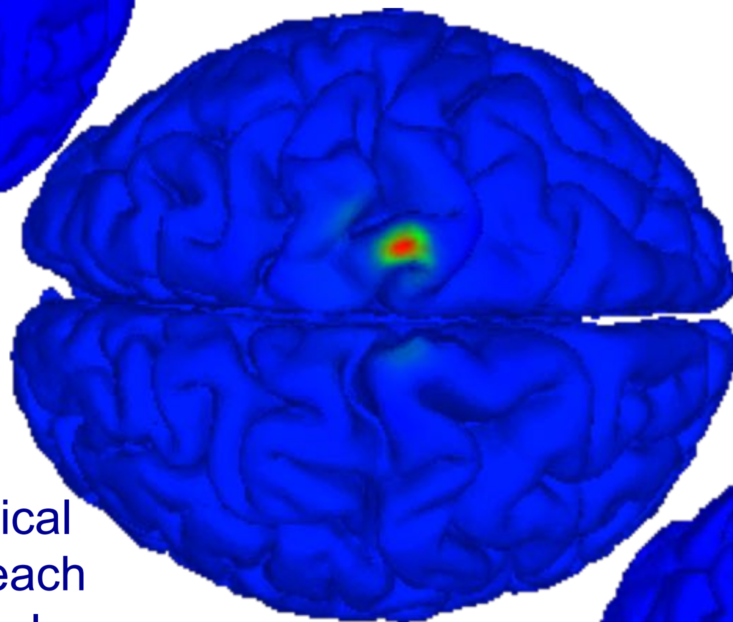
- The position of the source is not estimated as a whole
- Instead, On a pre-defined *source space* grid (3-D volume or cortical 2-D sheet)
  - Dipole strength is estimated *at each grid element*
  - In principle, a linear problem, easy to solve, BUT…
    - More "unknowns" (parameters) than "knowns" (channels, measurements), so …
    - An infinite number of solutions can explain the data perfectly (not necessarily physiologically plausible!)
  - **Therefore**, additional source constraints are required …

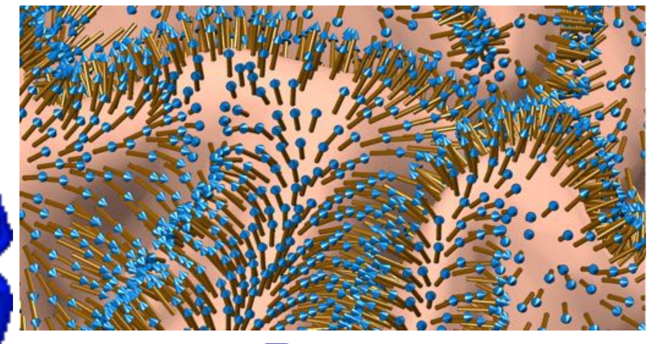
R. Oostenveld, & S. Makeig, 2016

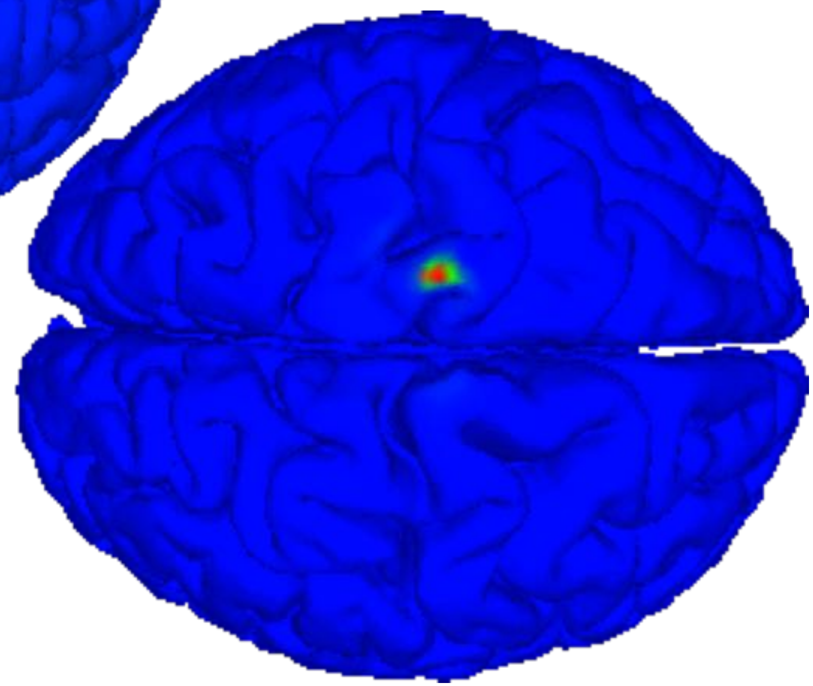
High-Resolution Distributed Source Localization

using a multiscale patch basis



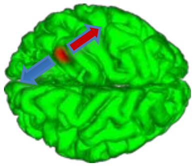






0. Build a high-res. cortical surface mesh; give each voxel an oriented dipole.
1. Compute a ‘dictionary’ of Gaussian patches conforming to the cortical surface centered at each cortical mesh voxel.
2. Use a ‘sparsifying’ approach to find the sum of the *fewest* of these patches that together produce the given source scalp or grid map.

Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16



Summary-1

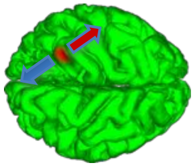
- An electromagnetic **forward head model** is required to interpret the sources of scalp maps
- Interpretation of scalp maps in terms of brain source distributions is "**inverse** source estimation"

→Mathematical techniques are available to aid in interpreting scalp maps as arising from particular brain sources

→ These require an **inverse source model**, i.e. assumptions about the possible locations and nature of the sources (i.e., what attributes make them ***physiologically plausible***).

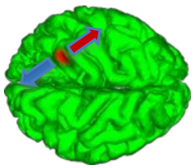
→ Then search for the ***most plausible*** source model.

R. Oostenveld, & S. Makeig, 2016



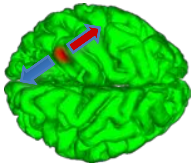
Summary-2

- **Inverse modeling**
  - Model assumption for volume conductor
  - Model assumption for source (I.e. dipole)
  - Additional assumptions on source
- **Single point-like sources**
- **Multiple point-like sources**
- **Distributed sources**
  - Different mathematical solutions
    - Dipole fitting (linear and nonlinear)
    - Linear estimation (regularized)



Summary-3

- **If we have MRI of the subject**
  - Subject specific head model
  - Distributed source localization
- **If we don’t have the MRI**
  - Warped 4-layer MNI model (NFT)
  - Dipole source localization
- **Skull conductivity estimation** is as important as the head model used (SCALE)
- White matter modeling does not have a huge effect on source localization – excepting deep sources ...



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