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

R. Oostenveld, & S. Makeig, 2016
Scalp dynamics ≠ source dynamics

Cortex

Equivalent Current Dipole

Local Synchrony

Relative Independence

Spatial EEG Source Filtering

S. Makeig 2007
EEG source modeling

**Source Space**
- electrical currents

**Forward problem**
- volume conduction through body tissues

**Inverse problem**
- Inverse localization method

**Sensor Space**
- recorded potentials

R. Oostenveld, & S. Makeig, 2016
Peri-neuronal currents

Closed field

Open field
Symmetry, orientation and activation

radially symmetric, i.e.
randomly-oriented

asynchronously activated

synchronously activated
parallel-oriented

Closed field

Phase cancellation

Open field

A when recorded at a distance, dipolar field components dominate
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 $\Rightarrow$ effective sources

R. Oostenveld, 2007
The equivalent current dipole
Equivalent current dipole modeling

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

A. Delorme, ~2007
Independent cortical components

- Single dipole component
- Dual-symmetric dipole component
- Equivalent dipoles
• 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).

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

Daunizeau, 2009
The linear forward problem (Daunizeau, 2009) where the lead field matrix giving potential vector contributions \(L\) to each scalp electrode for all possible source contributions \(S\) (source space). Anatomical constraint: Sources are in the cortex and 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 unstable?
  – Difficult for 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
- **Boundary Element Method**
  - description of head geometry by tissue compartments
  - Tissue in each compartment is assumed:
    - homogenous
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  - Important tissue types:
    - Scalp
    - Skull
    - CSF
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  - Each surface should be closed (no holes)

R. Oostenveld, & S. Makeig, 2016
Forward head models: Modeling the skull

- **Potential differences between electrodes** measures 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.

R. Oostenveld, & S. Makeig, 2016
Forward head models: Modeling the skull

• Problems with skull modeling
  – Poorly visible in the anatomic MRI (T2) image
  – Thickness varies regionally
  – Conductivity is not homogeneous
  – Complex geometry at front and base of skull

→ Skull conductivity variable & unknown
Volume conductor: FEM

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 & MRI Co-registration errors
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)

Mesh generation

Segmentation

Solve the forward problem using realistic head models (BEM)

Simple Map

Sensor Localization

Signal Processing

MRI

EEG/MEG

Source Image
The MNI Head Model

- 4-layer
  - 16856 nodes
  - 33696 elements

- 3-layer
  - 12730 nodes
  - 25448 elements
FEM models

BEM models

6-month old

adult

NFT

Akalin Acar & Makeig, 2010
NIST

Cheng Cao, 2012

Source space

Scalp map

Patch-based SBL

sLORETA

SCS

Load MRI
/start Freesurfer
/Cortical source space
/FP Solution with BEM
/FP Solution with FEM
/Component indices
/Select Source Localization Method
/Start Source Localization
/Visualization
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 (no longer in use)**
  - 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
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)
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

• 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

• 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

• 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.
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