Forward and inverse modelling and the EEGLAB dipfit tools

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Overview

Motivation and background
Forward modeling
  Source model
  Volume conductor model
Inverse modeling - general
  Single and multiple dipole fitting
  Distributed source models
  Beamforming methods
Inverse modeling - independent components
Summary
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Summary
Motivation 1

Strong points of EEG and MEG
- Temporal resolution (~1 ms)
- Characterize individual components of ERP
- Oscillatory activity
- Disentangle dynamics of cortical networks

Weak points of EEG and MEG
- Measurement on outside of brain
- Overlap of components
- Low spatial resolution
If you find a ERP/ERF component, you want to characterize it in physiological terms
   Time or frequency are the “natural” characteristics
   “Cortical location” requires interpretation of the scalp topography

Forward and inverse modeling helps to interpret the topography

Forward and inverse modeling helps to disentangle overlapping source timeseries
Superposition of source activity
Superposition of source activity

Timecourse of each source contributes to each channel

The contribution of each source to each channel depends on its “visibility”

Activity on each channel is a superposition of all source activity
Biophysical source modelling: overview

- **forward model**
  - physiological source electrical current
  - body tissue volume conductor
  - observed potential or field

- **inverse model**
Overview

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Summary
What produces the electric current
Equivalent current dipoles
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Summary
Volume conductor

described electrical properties of tissue

describes geometrical model of the head

describes how the currents flow, not where they originate from

same volume conductor for EEG as for MEG, but also tDCS, tACS, TMS, ...
Volume conductor

Computational methods for volume conduction problem that allow for realistic geometries

**BEM**  *Boundary Element Method*

**FEM**  *Finite Element Method*

**FDM**  *Finite Difference Method*
Volume conductor: Boundary Element Method

Each compartment is
    homogenous
    isotropic

Important tissues
    skin
    skull
    brain
    (CSF)

Triangulated surfaces describe boundaries
Volume conductor: Boundary Element Method

Construction of geometry
- segmentation in different tissue types
- extract surface description
- downsample to reasonable number of triangles
Volume conductor: Boundary Element Method

Construction of geometry
  segmentation in different tissue types
  extract surface description
  downsample to reasonable number of triangles

Computation of model
  independent of source model
  only one lengthy computation
  fast during application to real data

Can (almost) be arbitrary complex
Volume conductor: Finite Element Method

Tessellation of 3D volume in tetraeders or hexaheders
Volume conductor: Finite Element Method

tetraeders

hexaheders
Volume conductor: Finite Difference Method

Easy to compute

Not very useful
Volume conductor: Finite Difference Method

\[
\frac{V_1 - V_0}{R_1} + \frac{V_2 - V_0}{R_2} + \frac{V_3 - V_0}{R_3} + \frac{V_4 - V_0}{R_4} = 0
\]

\[
I_1 + I_2 + I_3 + I_4 = 0
\]

\[
V = I \cdot R
\]

\[
\Delta V_1 / R_1 + \Delta V_2 / R_2 + \Delta V_3 / R_3 + \Delta V_4 / R_4 = 0
\]

\[
(V_1 - V_0)/R_1 + (V_2 - V_0)/R_2 + (V_3 - V_0)/R_3 + (V_4 - V_0)/R_4 = 0
\]
Volume conductor: Finite Difference Method

Unknown potential $V_i$ at each node
Linear equation for each node
  approx. $100 \times 100 \times 100 = 1,000,000$ linear equations
  just as many unknown potentials

Inject some current $+I$ and $-I$ at two of the nodes

Solve for unknown potential
EEG volume conduction
EEG volume conduction

Potential difference between electrodes corresponds to current flowing through skin

Only tiny fraction of current passes through skull

Therefore the model should describe the skull and skin as accurately as possible
MEG volume conduction

MEG measures magnetic field over the scalp

Magnetic field itself is not distorted by skull but also from the volume currents

Only tiny fraction of current passes through skull, therefore the model can ignore the skull and...
Practical differences between EEG and MEG

fixed sensor positions in MEG
flexible cap in EEG

MEG requires head size to be known in analysis using individual anatomical MRI
position of sensors is accurately known

EEG requires the electrode positions to be known in analysis
Obtaining geometrical data
3D scanning instead of MRI
3D scanning - pipeline for EEG modelling

Surface scan

Individualised template
3D scanning
3D scanning - Electrode position accuracy

optimized template
standard template
individual 3D scan

Homölle & Oostenveld in preparation
Forward modeling – practical considerations

- **Most accurate** source estimate using individual headmodels and electrode positions
- **Decent accurate** source estimate with template headmodel and individual electrode positions
- **Reasonably accurate** source estimate with template BEM headmodel and template electrodes
- **Least accurate** source estimate with spherical model and template electrodes
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  EEG versus MEG

**Inverse modeling - general**
  Single and multiple dipole fitting
  Distributed source models
  Beamforming methods

Inverse modeling - independent components

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Biophysical source modelling: overview

**forward model**

physiological source electrical current → body tissue volume conductor → observed potential or field

**inverse model**
Inverse methods

Single and multiple dipole models
Minimize error between model and measured potential/field

Distributed source models
Perfect fit of model to the measured potential/field
Additional constraint on source smoothness, power or amplitude

Spatial filtering
Scan the whole brain and compute filter output at every location
Beamforming (e.g. LCMV, SAM, DICS)
Multiple Signal Classification (MUSIC)
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Inverse localization: demo
Single or multiple dipole models - Parameter estimation

\[ y = f(x; a, b, c, \ldots) \]

- \( y \) = potential
- \( x \) = electrode positions
- \( f() \) = forward model
- \( a, b, c \) = source parameters
Parameter estimation: dipole parameters

source model with few parameters
  position
  orientation
  strength

compute the model data

minimize difference between actual and model data

\[ y = f(x; a, b) = a \times x + b \]
Non-linear parameters: grid search

One dimension, e.g. location along medial-lateral
100 possible locations

Two dimensions, e.g. med-lat + inf-sup
100x100 = 10,000

Three dimensions
100x100x100 = 1,000,000 = 10^6

Two dipoles, each with three dimensions
100x100x100x100x100x100 = 10^{12}
Optimization of non-linear parameters

\[
\text{error}(x, y, z) = \sum_{i=1}^{N} (Y_i(x, y, z) - V_i)^2 \Rightarrow \min_{x, y, z} (\text{error}(x, y, z))
\]
Single or multiple dipole models - Strategies

Single dipole:
  scan the whole brain, followed by iterative optimization

Two dipoles:
  scan with symmetric pair, use that as starting point for iterative optimization

More dipoles:
  sequential dipole fitting
Sequential dipole fitting for ERPs

Assume that activity starts “small”
- explain earliest ERP component with single equivalent current dipole

Assume later activity to be more widespread
- add ECDs to explain later ERP components
- estimate position of new dipoles
- re-estimate the activity of all dipoles
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Distributed source model

Position of the source is **not estimated** as such

Pre-defined grid (3D volume or on cortical sheet)

**Strength is estimated**

- In principle easy to solve, however...
- More “unknowns” (parameters) than “knowns” (measurements)
- Infinite number of solutions can explain the data perfectly
- Additional constraints required
Distributed source model
Distributed source model
Distributed source model: linear estimation

distributed source model with **many dipoles** throughout the whole brain

estimate the strength of all dipoles

data and noise can be perfectly explained

\[ y = f(x; a_1, a_2 \ldots a_N) \]
Distributed source model: regularization

\[ V = G \cdot q + \text{Noise} \]

\[ \min_q \{ \| V - G \cdot q \|^2 \} = 0 !! \]

Regularized linear estimation:

\[ \rightarrow \min_q \{ \| V - G \cdot q \|^2 + \lambda \cdot \| D \cdot q \|^2 \} \]

- mismatch with data
- mismatch with prior assumptions
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Summary
Scanning with a beamformer filter
Spatial filtering with beamforming

Position of the source is **not estimated** as such

Manipulate filter properties, not source properties

No explicit assumptions about source constraints
  (implicit: single dipole)

Assumption that sources that contribute to the data should be uncorrelated
Spatial filtering with beamforming

\[ w^T G^* = 1 \]

\[ w^T G = 0 \]
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**Inverse modeling - independent components**

Summary
Independent component analysis

Cocktail Party

Mixture of Brain source activity
Independent component analysis

\[ Y = [A; B] \]

Linear Combination

\[ x = Wy \]

ICA

\[ y \sim w \sim x \]

Source

\[ \sim \]
Cortex
Skin
Electrodes

local synchr.
relative independence
local synchr.
Estimating source timecourse activity

\[ Y = G_1X_1 + G_2X_2 + \ldots + G_nX_n + \text{noise} \]

\[ X'(t) = W Y(t) \]

distributed sources

each at a time

few sources

dipole fitting

minimum norm estimate

all brain (and artifact) sources

beamforming

independent component analysis
Source modelling of independent components

ICA takes care of unmixing of timeseries
Source analysis to take care of the location

Assumption: components correspond to compact spatial patches (or bilateral patches)

Use simple dipole models to model the spatial component topographies
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  Spatial filtering

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Forward modelling
Required for the interpretation of scalp topographies
Different methods with varying accuracy

Inverse modelling
Estimate 1) location and 2) timecourse

Assumptions on source locations
Single or multiple point-like source
Distributed source

Assumptions on source timecourse
Uncorrelated (and dipolar)
Independent
Independent component analysis separates topography and timecourse

Inverse methods to interpret topography
   Single or multiple point-like source
   Distributed source

Temporally independent component topographies are often dipolar
Summary 3

EEGLAB dipfit plugin
  head model
  grid search
  non-linear optimization

Results in equivalent current dipole location for each component topography