Hierarchical Bayesian Models for Focal EEG/MEG Inversion

"Innovative Verarbeitung bioelektrischer und biomagnetischer Signale" - bbs2012
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Background of the Talk

Felix Lucka., Sampsa Pursiainen, Martin Burger, Carsten H. Wolters.
Hierarchical Bayesian Inference for the EEG Inverse Problem using Realistic FE Head Models: Depth Localization and Source Separation for Focal Primary Currents.
Neuroimage, accepted.

Felix Lucka.
Hierarchical Bayesian Approaches to the Inverse Problem of EEG/MEG Current Density Reconstruction.
Diploma thesis in mathematics, University of Münster, March 2011
Depth Bias and Masking in EEG/MEG

Recovery of brain networks involving
- multiple,
- focal,
- possibly deep-lying sources.

Very important for the analysis of neurophysiological data and in clinical applications.

Unknown number and spatial extend of sources?

→ Current density reconstruction (CDR).

Problems of established CDR methods:
- **Depth-Bias**: Reconstruction of deeper sources too close to the surface.
- **Masking**: Near-surface sources “mask” deep-lying ones.
Depth Bias: Illustration

One deep-lying reference source (blue cone) and minimum norm estimate (MNE, Hämäläinen and Ilmoniemi, 1994).
Depth Bias: Illustration
One deep-lying reference source (blue cone) and sLORETA result (Pascual-Marqui, 2002).
Masking: Illustration

Reference sources.
Masking: Illustration
MNE result and reference sources (green cones).
Masking: Illustration
sLORETA result and reference sources (green cones).
Hierarchical Bayesian Modeling (HBM) for CDR

David Wipf and Srikantan Nagarajan.  
A unified Bayesian framework for MEG/EEG source imaging.  
Neuroimage, 44(3):947-66, February 2009

Key features (proper introduction is behind the scope of this talk...):

- Further development of weighted minimum norm schemes.
- Flexible framework for embedding qualitative and quantitative a-priori information.
- Automatic selection of important features.
- Comprises former methods like MNE, WMNE, LORETA, sLORETA, FOCUSS, MCE,...
- New ways of inference: Full-MAP, Full-CM, $\gamma$-MAP, S-MAP, VB
Key Question

Starting point:

- A specific HBM aims to recover source configurations consisting of few, focal sources (introduced in Sato et al., 2004; further examined in Nummenmaa et al., 2007; Wipf and Nagarajan, 2009; Calvetti et al., 2009)
- Calvetti et al., 2009 found promising first results with Full-MAP and Full-CM estimation for deep-lying sources and separation of multiple (focal) sources.

Limitations of Calvetti et al., 2009:

- Full-MAP results were not convincing; reason unclear.
- No systematic examination; only two source scenarios.
- Head models insufficient.
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Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

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Own Contributions/Work

Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

Work program:

▶ Implementation of Full-MAP and Full-CM inference for HBM with realistic, high resolution Finite Element (FE) head models.
▶ Propose own algorithms for Full-MAP estimation.
▶ Introduction of suitable performance measures for validation of simulation studies.
▶ Systematic examination of performance concerning depth-bias and masking in simulation studies.

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Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-CM result.
Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-MAP result proposed by Calvetti et al., 2009.
Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-MAP result proposed by us.
Results Masking: Illustration

Full-CM result and reference sources (green cones).
Results Masking: Illustration

Full-MAP result (by our algorithm) and reference sources (green cones).
Systematic Studies: Summary

Study 1 (depth-bias):
- Reconstruction of single 1000 dipoles; random location and orientation.
- Reconstructions were compared using different performance measures.
- Specific examination of depth bias.

Study 2 (masking):
- Reconstruction of 1000 source configurations consisting of one near-surface and one deep-lying dipole.
- Reconstructions were compared using a new performance measure based on optimal transport (called earth mover’s distance, a Wasserstein metric).

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Systematic Studies: Summary

Results for Full-MAP and Full-CM estimation:
- Good performance in all validation measures.
- No depth bias.
- Good results w.r.t. orientation, amplitude and spatial extend.
- Full-MAP estimate (by our algorithm): Best results in every aspect examined.

⇒ Full results:
Conclusions

Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?
Conclusions

Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

Results

- Hierarchical Bayesian modeling used with realistic head modeling is a promising framework for EEG/MEG CDR.
- Promising results for deep sources (no depth bias).
- Promising results for challenging multiple source scenarios (no masking).

★ A promising tool for the analysis of neurophysiological data. ★

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Work in Progress and Outlook

- Analysis of real data, e.g., tonotopy & auditory pathway reconstruction
- Temporal extension
- Extension to extended source scenarios
- Comparison to other HBM-based methods
- Interplay of HBM and more realistic head modeling
- Multimodal integration: EEG, MEG, PET, SPECT, fMRI, DW-MRI...
Main References

David Wipf and Srikantan Nagarajan.  
A unified Bayesian framework for MEG/EEG source imaging.  
Neuroimage, 44(3):947-66, February 2009

Daniela Calvetti, Harri Hakula, Sampsa Pursiainen, and Erkki Somersalo.  
Conditionally Gaussian hypermodels for cerebral source localization.  

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Hierarchical Bayesian Approaches to the Inverse Problem of EEG/MEG  
Current Density Reconstruction.  
Diploma thesis in mathematics, University of Münster, March 2011

Felix Lucka., Sampsa Pursiainen, Martin Burger, Carsten H. Wolters.  
Hierarchical Bayesian Inference for the EEG Inverse Problem using Realistic  
FE Head Models: Depth Localization and Source Separation for Focal  
Primary Currents.  
Neuroimage, accepted.
Thank you for your attention!

Software used by our group:

- Registration: FSL, FAIR;
- Segmentation: FSL, CURRY;
- FEM Meshing: Tetgen, vgrid, iso2mesh;
- FEM Computation: SimBio;
- Data Preprocessing: CURRY, BESA;
- Inverse computation: Matlab;
- Volume Visualization: SCIRun;
- Everything else & software integration: Matlab;

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Three Dipoles: MNE
Three Dipoles: MNE, threshold = 30%
Three Dipoles: MNE, threshold = 50%
Three Dipoles: MNE, threshold = 70%
Three Dipoles: sLORETA
Three Dipoles: sLORETA, threshold = 30%
Three Dipoles: sLORETA, threshold = 50%
Three Dipoles: sLORETA, threshold = 70%
Three Dipoles: Full-CM
Three Dipoles: Full-MAP
Head Model Generation Pipeline

registration
segmentation
extract, repair & smooth surfaces
volume meshing
source space construction
forward computation

\[
\begin{pmatrix}
L_{11} & L_{12} & \cdots & L_{1n} \\
L_{21} & L_{22} & \cdots & L_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
L_{m1} & L_{m2} & \cdots & L_{mn}
\end{pmatrix}
\]
Realistic Tetrahedron Head Model

- Compartments: Skin, eyes, skull compacta and skull spongiosa, inner brain.
- 512,394 FEM nodes and 3,176,162 tetrahedra
Realistic and Artificial Sensor Configurations

Red spheres: Realistic sensor configuration (63 electrodes); Red and blue spheres: Artificial sensor configuration (134 electrodes).
Source Space Grid

1000 source space nodes based on a regular grid.
Studies: Source Space Grid

1000 source space nodes based on a regular grid.
Depth Bias Study: Average Results (considered in this talk)

- 1000 dipoles; random location and orientation.
- Noise level 5%.
- Mean distance from reference source to next source space node: 5.27 mm.

<table>
<thead>
<tr>
<th>Method</th>
<th>EMD</th>
<th>DLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNE</td>
<td>53.20 / 54.90 mm</td>
<td>29.46 / 33.07 mm</td>
</tr>
<tr>
<td>sLORETA</td>
<td>40.58 / 43.43 mm</td>
<td>6.10 / 6.60 mm</td>
</tr>
<tr>
<td>CM</td>
<td>7.26 / 8.85 mm</td>
<td>6.21 / 6.94 mm</td>
</tr>
<tr>
<td>MAP1</td>
<td>28.18 / 32.77 mm</td>
<td>27.00 / 33.76 mm</td>
</tr>
<tr>
<td>MAP2</td>
<td>5.83 / 6.15 mm</td>
<td>5.78 / 6.14 mm</td>
</tr>
</tbody>
</table>

- EMD: *Earth mover’s distance*; performance measure based on *optimal transport* (a *Wasserstein metric*).
- DLE: *Dipole localization error*; Distance from reference source to source space node with maximal amplitude (standard performance measure).

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Depth Bias Study: Scatter Plots, Explanation

- Depth of the real source
- Depth of the estimated source
- Drift into depth
- Drift to surface
- Localized
- The
- Right
- Depth
- Drift to surface

The graph illustrates the relationship between the depth of the real source and the depth of the estimated source, showing how drift into depth and drift to surface can affect the localization of sources.
Depth Bias Study: Scatter Plots, MNE, artificial cap
Depth Bias Study: Scatter Plots, sLORETA, artificial cap
Depth Bias Study: Scatter Plots, Full-CM, artificial cap
Averaged Results

- 1000 source configurations consisting of one near-surface and one deep-lying dipole.
- Noise at a noise level of 5%.

<table>
<thead>
<tr>
<th>Method</th>
<th>EMD</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNE</td>
<td>44.63 / 45.75 mm</td>
</tr>
<tr>
<td>WMNE-$\ell_2$</td>
<td>43.75 / 44.62 mm</td>
</tr>
<tr>
<td>WMNE-reg-$\ell_\infty$</td>
<td>41.79 / 42.78 mm</td>
</tr>
<tr>
<td>sLORETA</td>
<td>36.38 / 38.07 mm</td>
</tr>
<tr>
<td>CM</td>
<td>14.57 / 18.21 mm</td>
</tr>
<tr>
<td>MAP1</td>
<td>42.10 / 47.97 mm</td>
</tr>
<tr>
<td>MAP2</td>
<td>12.41 / 15.83 mm</td>
</tr>
</tbody>
</table>

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