MRC Cognition and Brain Sciences Unit

UNIVERSITY OF CAMBRIDGE

EEG/MEG 2:

Spatial Resolution and Nonlinear Methods

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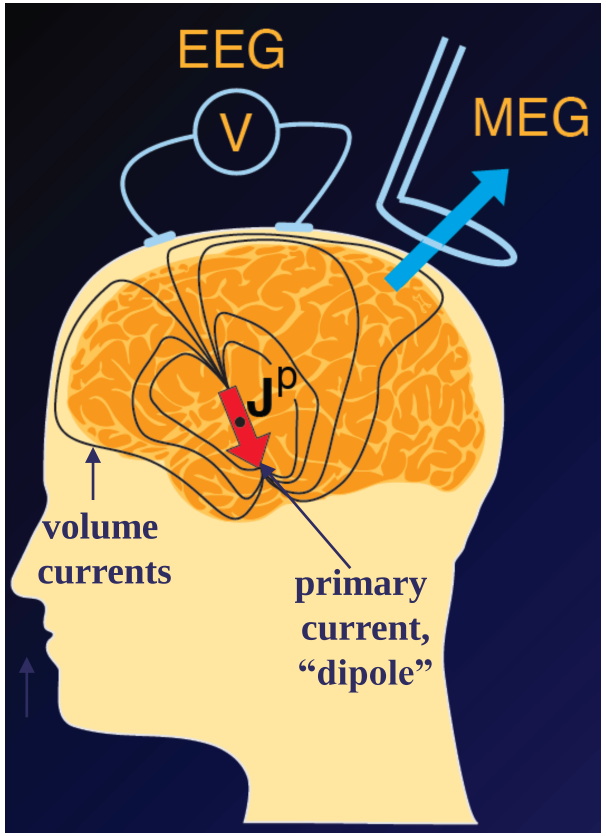
COGNESTIC 2023

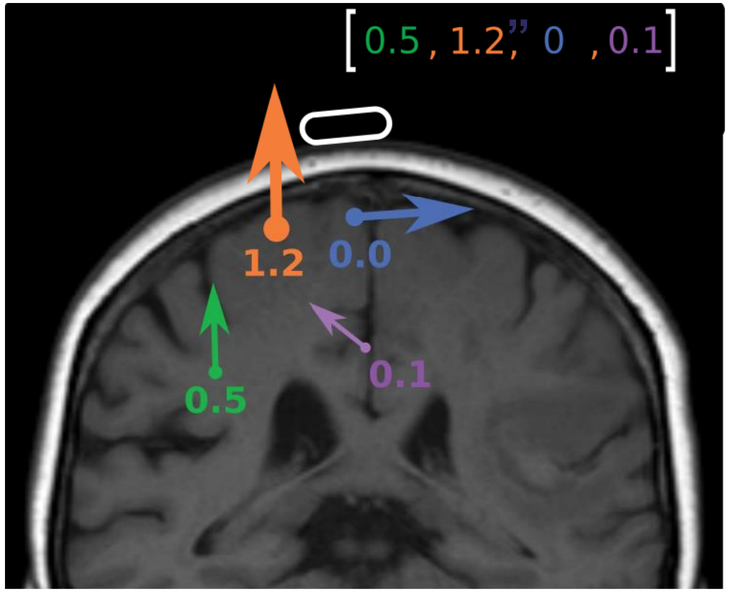
The EEG/MEG Forward Problem

EEG/MEG measure the primary sources indirectly



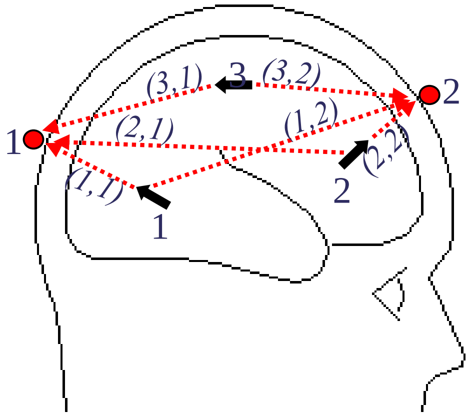
Sensors are differently sensitive to different sources

“Leadfield”



Hauk, Strenroos, Treder. In: Supek S, Aine C (edts), “Magnetoencephalography: From Signals to Dynamic Cortical Networks, 2nd Ed.”

We Have To First State The Forward Problem In Order To Solve The Inverse Problem



Inverse Operator

data "leadfield" dipoles

$$\begin{array}{c} 1 \\ 2 \end{array} \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} = \begin{pmatrix} 0.5 & 0 & 0.3 \\ 0 & 1 & -0.3 \end{pmatrix} \begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \end{array}$$

?

inversion

dipoles inverse data

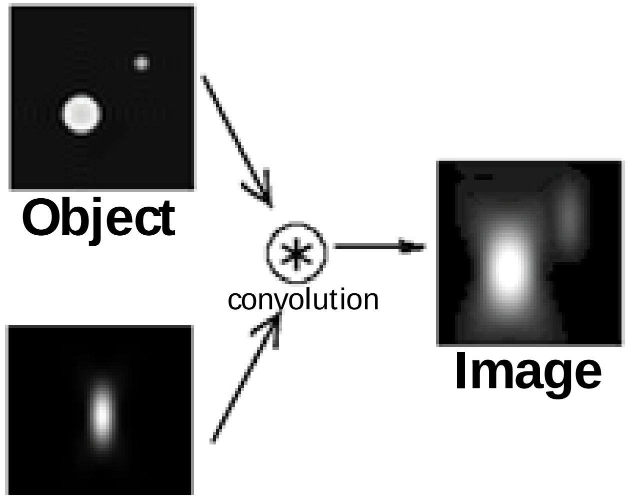
$$\begin{array}{c} 1 \\ 2 \\ 3 \end{array} \begin{pmatrix} j_1 \\ j_2 \\ j_3 \end{pmatrix} = \begin{pmatrix} 1.5034 & 0.1241 \\ 0.2483 & 0.9379 \\ 0.8276 & -0.2069 \end{pmatrix} * \begin{pmatrix} d_1 \\ d_2 \end{pmatrix} \begin{array}{c} 1 \\ 2 \end{array}$$

Let's Start Again:
The "Blurry Image" Analogy

Just because the brain is complicated doesn't mean source estimation has to be complicated

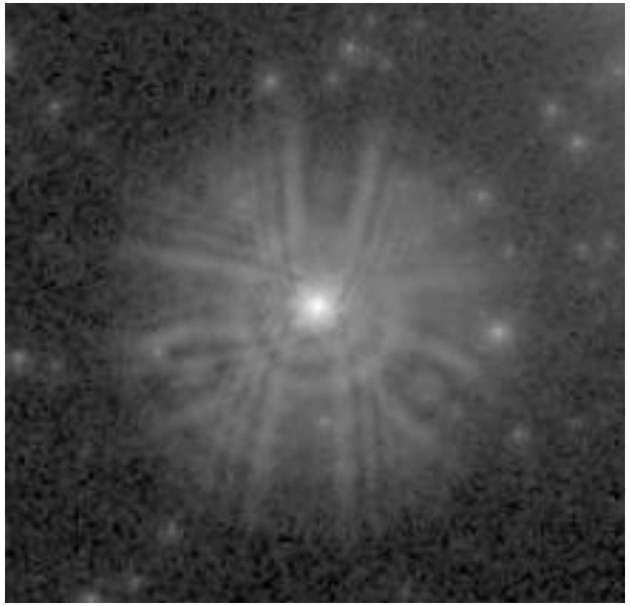
The Superposition Principle
A “Constraint-Free” Interpretation of Linear Methods

Microscopy



Point-Spread Function
PSF

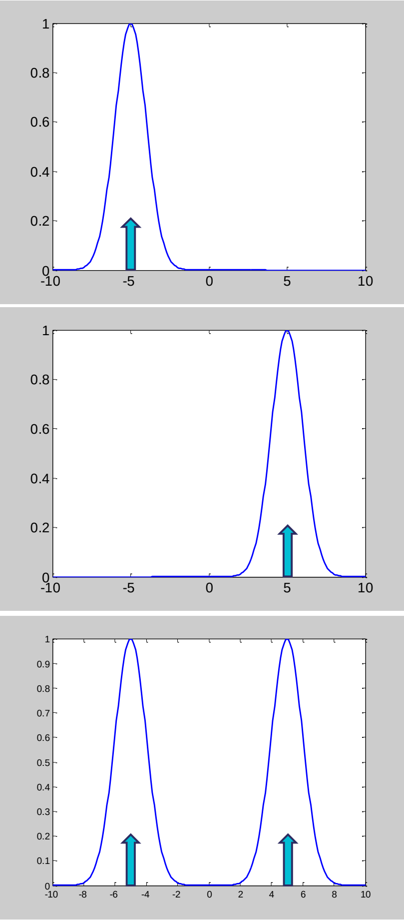
Astronomy

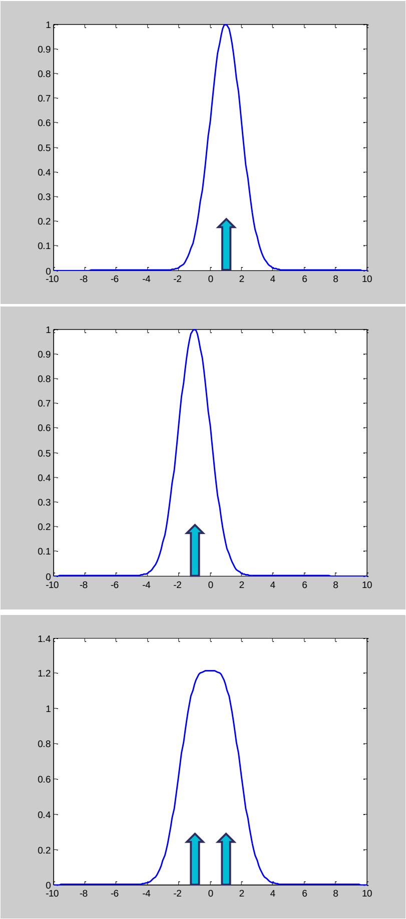


https://en.wikipedia.org/wiki/Point_spread_function

Linear Methods Can Easily Tell Us If They Do What We Want

Superposition Principle

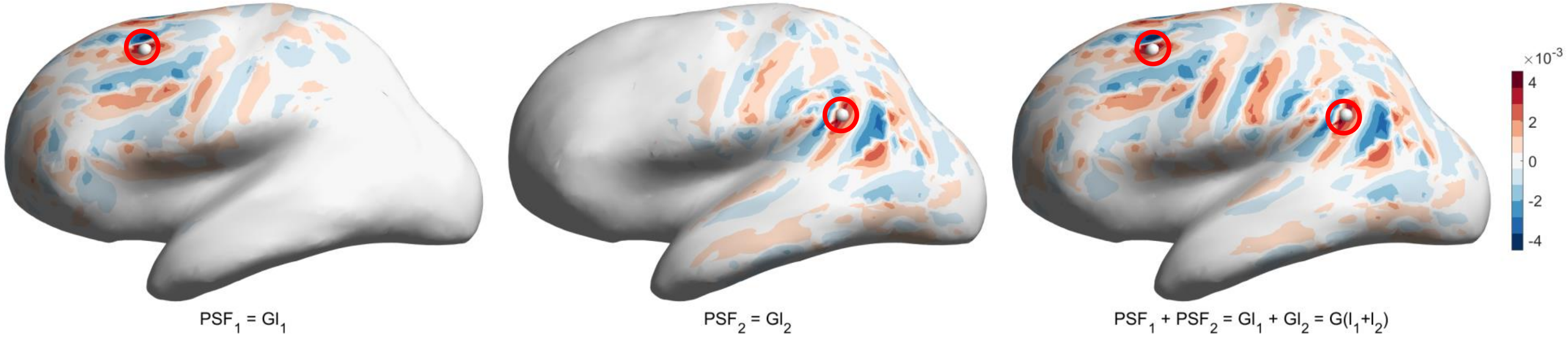




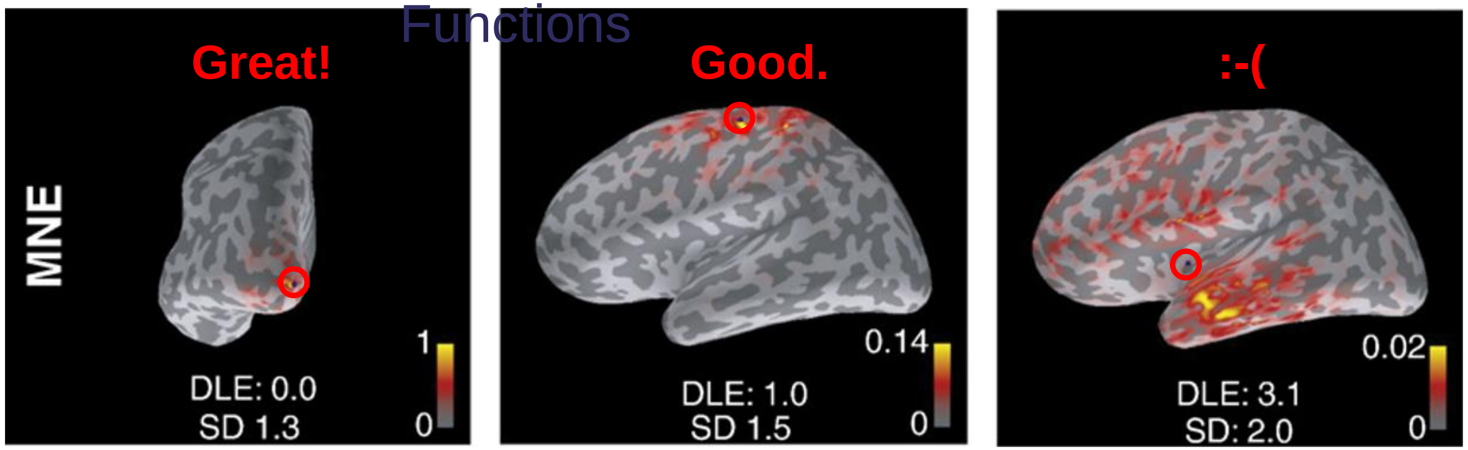
If you know the behaviour for point sources,
you can predict the behaviour for complex sources

Linear Methods – Superposition Principle

Superposition In Source Space



Example Point-Spread Functions



Hauk, Strenroos, Treder. In: Supek S, Aine C (edts), “Magnetoencephalography:

Spatial Resolution of Source Estimation Is Complex

Spatial resolution depends on:

number of sensors (EEG/MEG or both)

source location

source orientation

signal-to-noise ratio

head modelling

assumptions about the sources

=> difficult to make general statement

Resolution Matrix

Forward Problem **Linear Inverse Problem**

$$\mathbf{d} = \mathbf{L}\mathbf{s}$$

$$\hat{\mathbf{s}} = \mathbf{G}\mathbf{d}$$

$$\hat{\mathbf{s}} = \mathbf{G}\mathbf{L}\mathbf{s} \stackrel{\text{def}}{=} \mathbf{R}\mathbf{s}$$

Relationship between estimated and true source distribution.

e.g. Hauk/Stenroos/Treder, bioRxiv 2019
https://www.biorxiv.org/content/10.1101/672956v1

Creating an Optimal Resolution Matrix

$$\hat{\mathbf{s}} = \mathbf{R}\mathbf{s}$$

The closer **R** is to the identity matrix, the closer our estimate is to the true source.

Therefore, let us minimise the difference between **R** and the identity matrix in the least-squares sense:

$$\|\boldsymbol{R} - \boldsymbol{I}\|_2 = min$$

This leads to the **Minimum Norm Estimator (MNE)**:

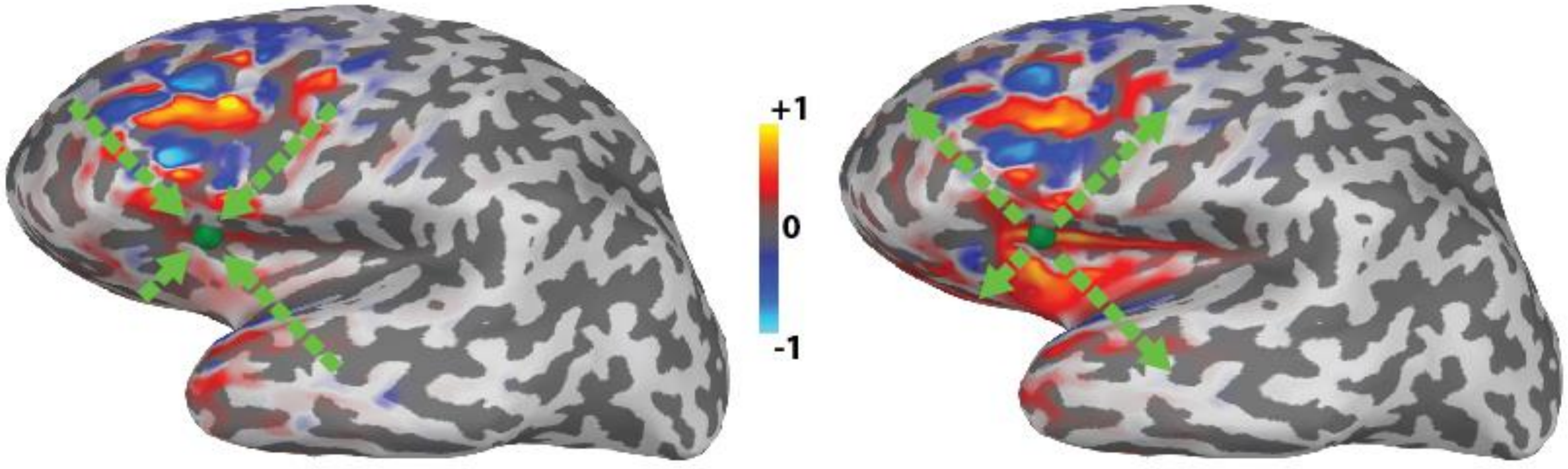
$$\boldsymbol{G}_{\boldsymbol{MN}} = \mathbf{L}^T(\mathbf{L}\mathbf{L}^T)^{-1}$$

Its resolution matrix $\boldsymbol{R}_{\boldsymbol{MN}} = \mathbf{L}^T(\mathbf{L}\mathbf{L}^T)^{-1}\mathbf{L}$ is symmetric.

e.g. Hauk/Stenroos/Treder, bioRxiv 2019
https://www.biorxiv.org/content/10.1101/672956v1

Spatial Resolution / Leakage:
Point-Spread and Cross-Talk

Cross-Talk Function (CTF) | Point-Spread Function (PSF)

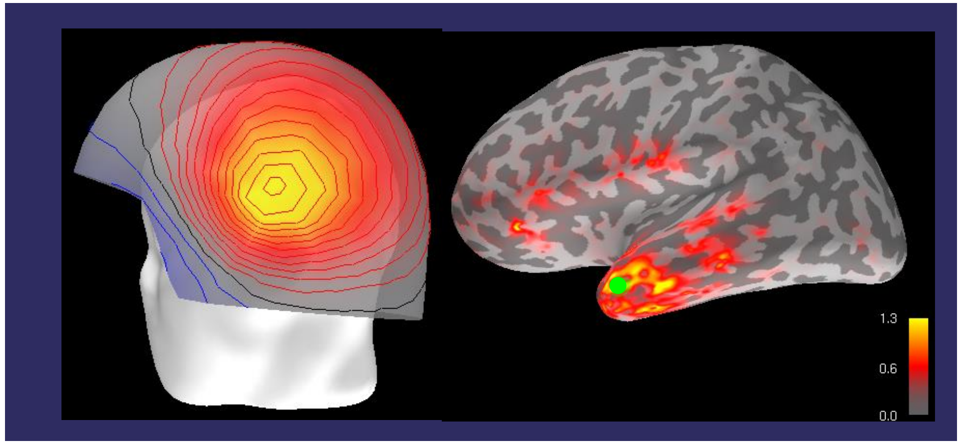


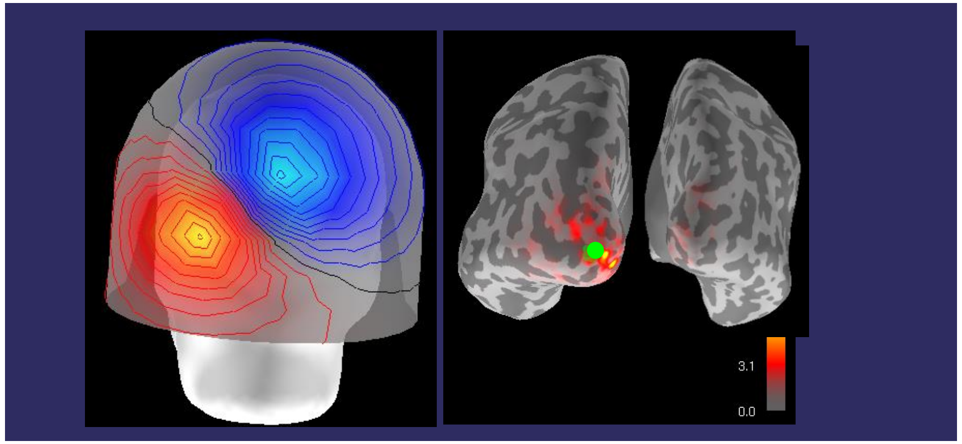
How other sources may affect the estimate for this source | *How this source affects estimates for other sources*

e.g. Hauk, Stenroos, Treder, Neuroimage 2022
https://www.sciencedirect.com/science/article/pii/S1053811922002993

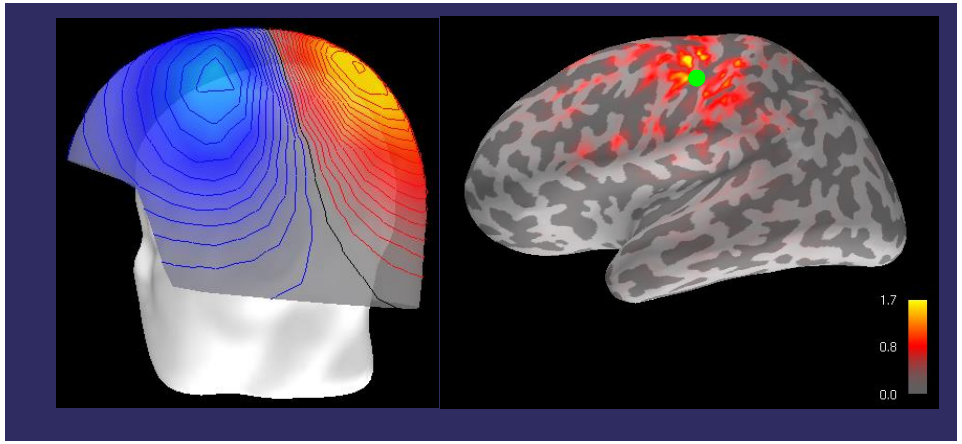
PSFs and CTFs for Some ROIs

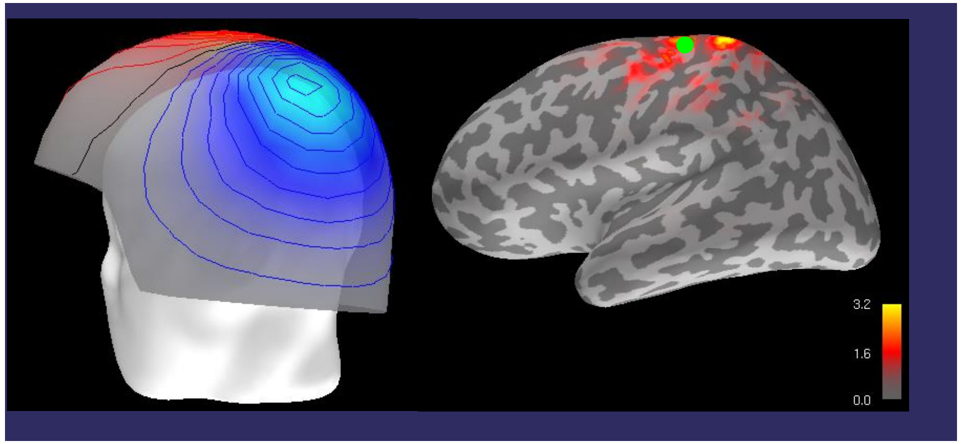
For MNE, PSFs and CTFs turn out to be the same





Good





PSFs and CTFs for Some ROIs

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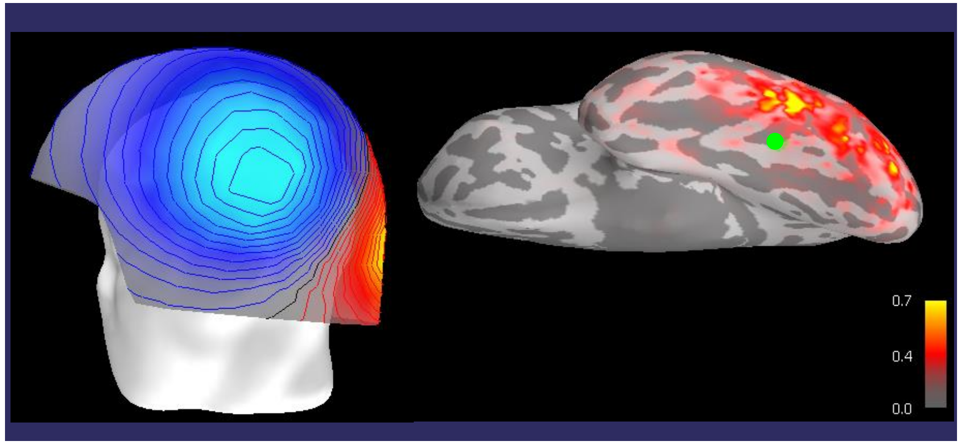
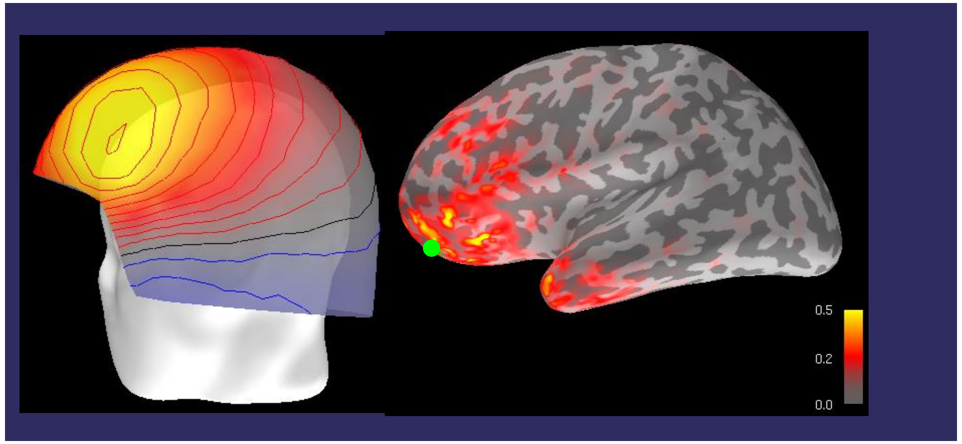
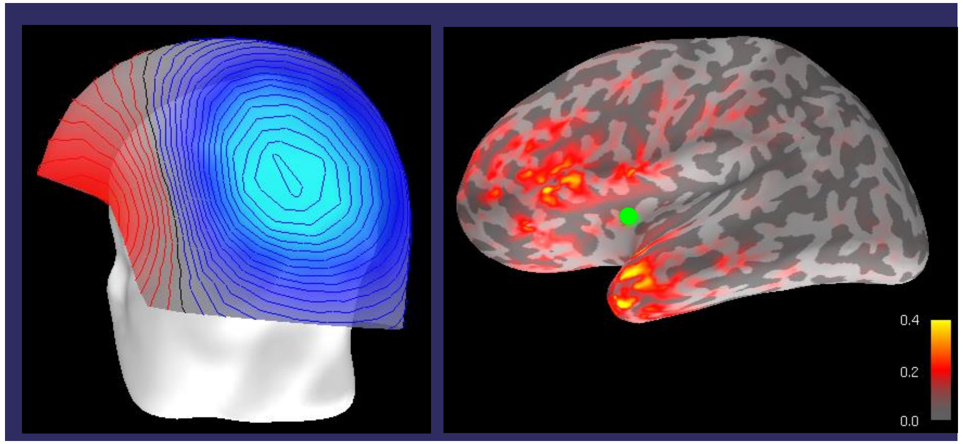


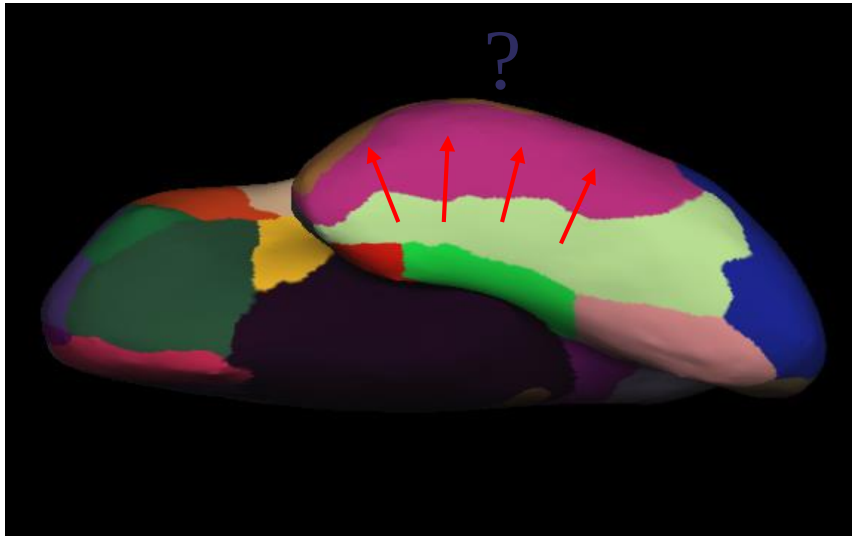


Less good

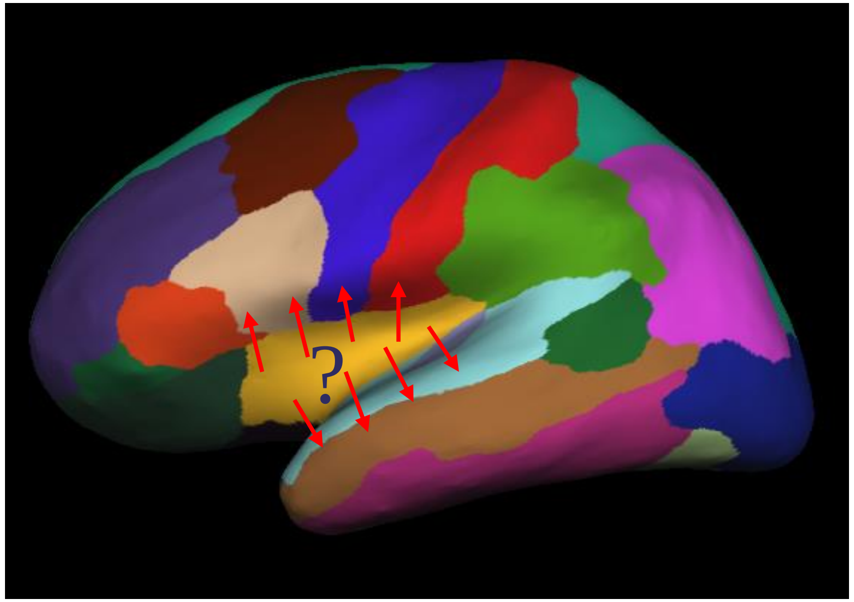


Localisation Bias Has Consequences for ROI analysis

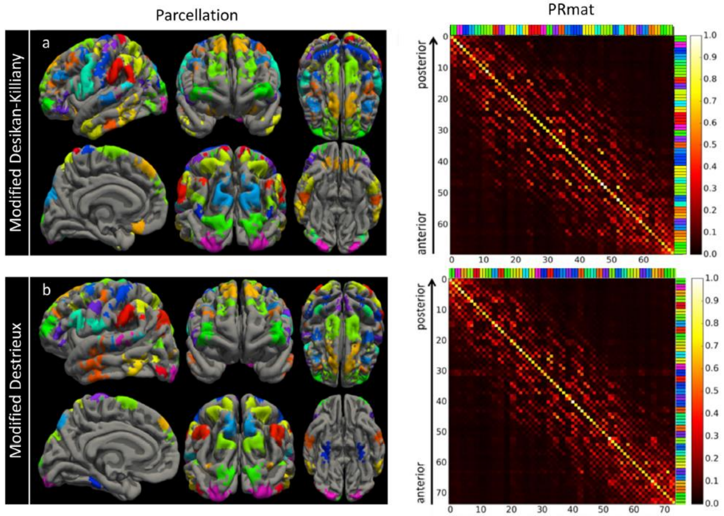
PSFs/CTFs Can Tell You How It Looks Like



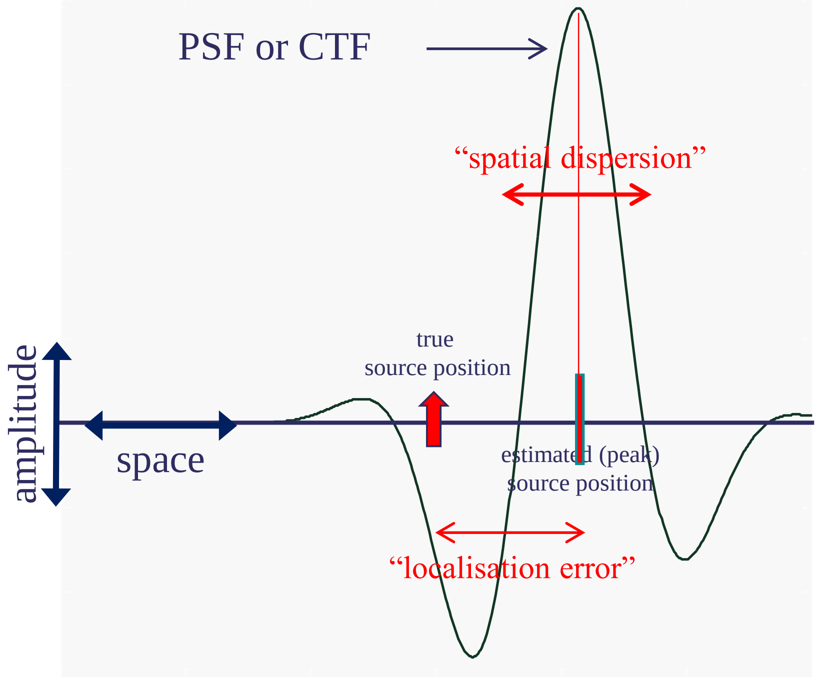
Desikan-Killiany Atlas parcellation

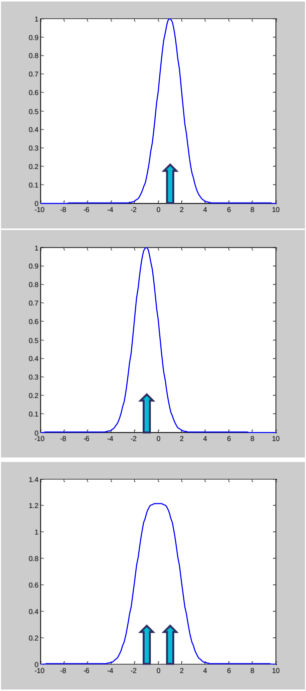


Adaptive cortical parcellation based on resolution matrix are possible: Farahibozorg/Henson/Hauk NI 2018 https://pubmed.ncbi.nlm.nih.gov/28893608/



Quantifying Resolution From PSFs and CTFs

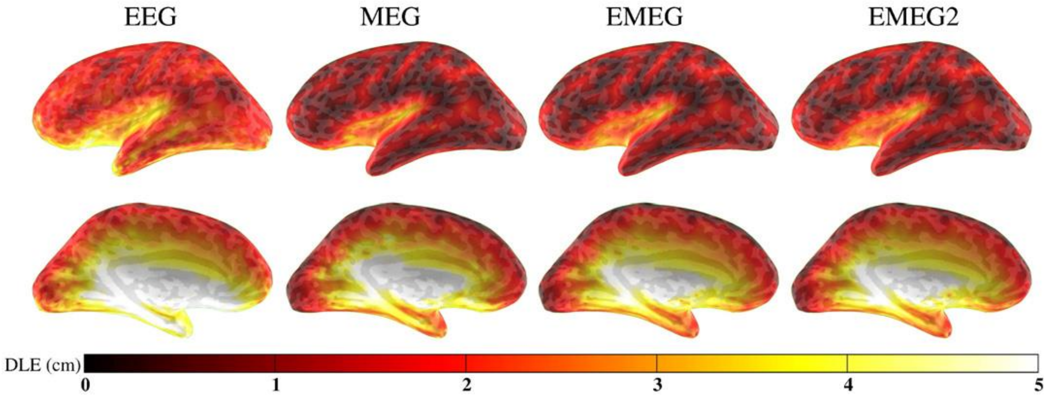




It's not just peak localisation that counts, but also spatial extent of the distribution.

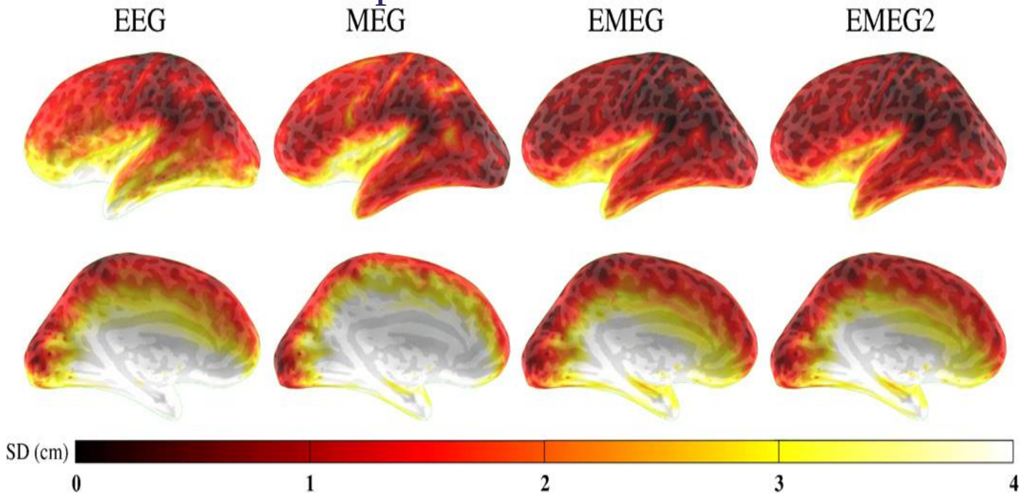
Whole-Brain Maps of Resolution Metrics

Peak Localization Error



Molins et al., Neuroimage 2008

Spatial Deviation



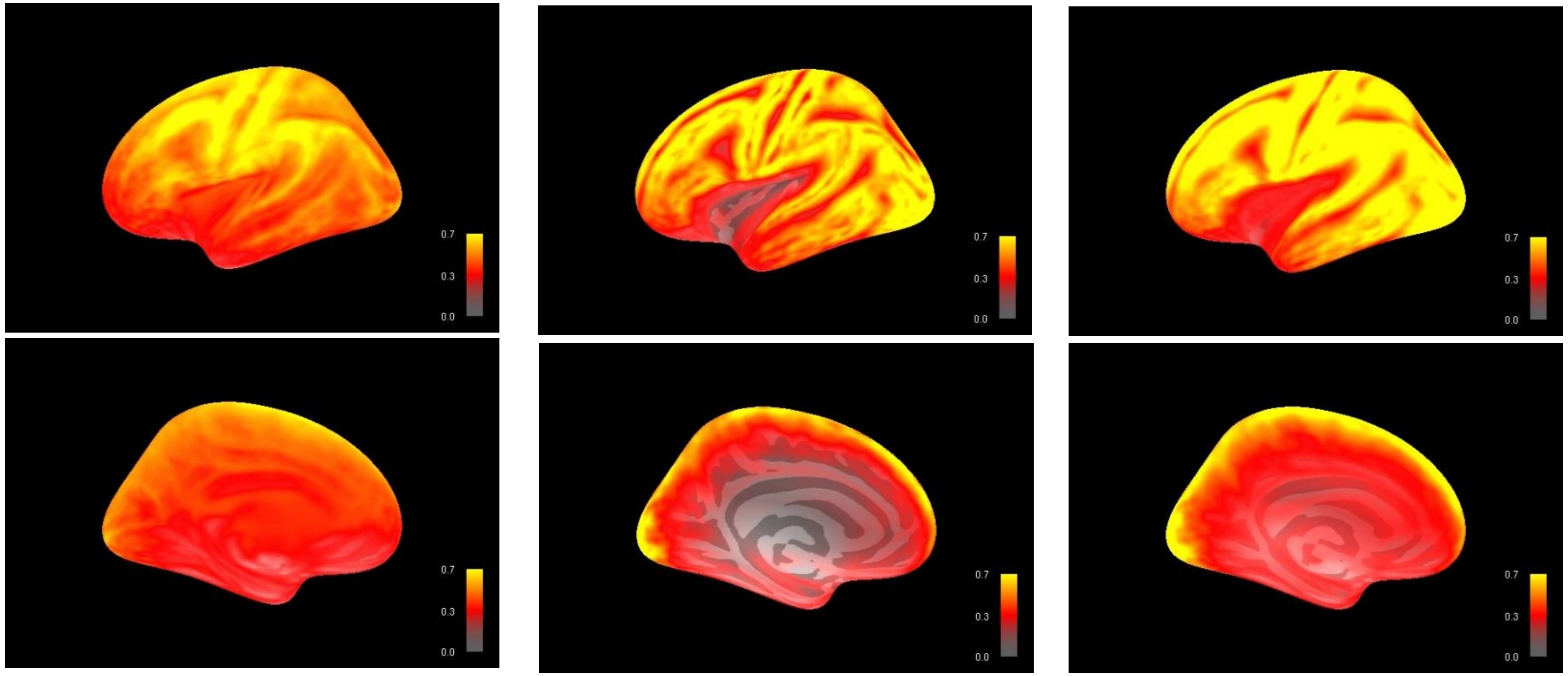
Combining EEG and MEG improves spatial resolution.

Sensitivity Maps
RMS of Leadfield Columns

EEG
70 electrodes

MEG
102 mags + 204 grads

EEG+MEG
102 mags + 204 grads



Combining EEG and MEG improves sensitivity.

Also: Goldenholz et al, HBM 2009

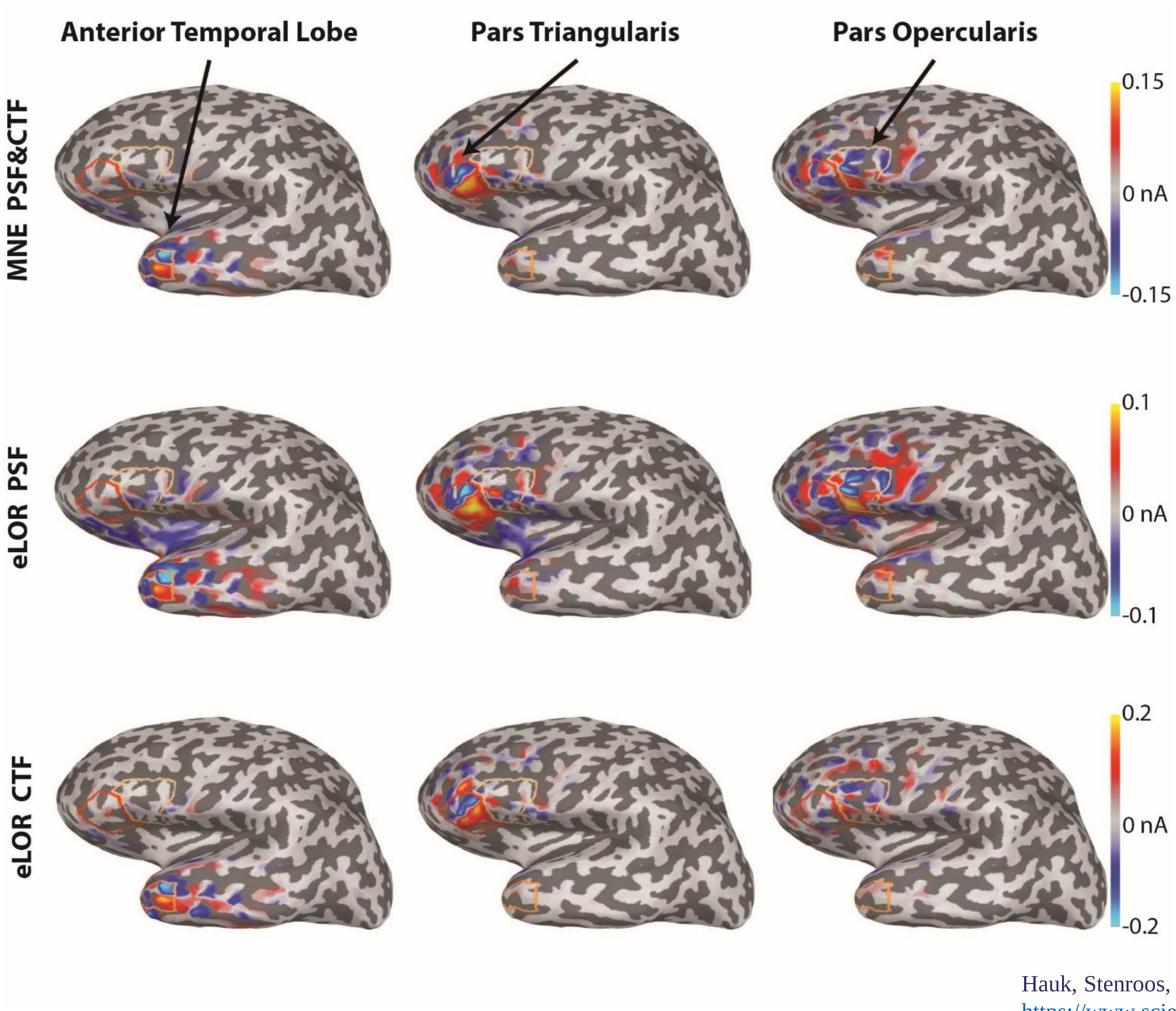
Methods Comparison

- **MEG+EEG**: Elekta Vectorview (360+70 channels), Wakeman & Henson open data set
- **Methods**:
  - L2-MNE
  - depth-weighted L2-MNE
  - dSPM
  - sLORETA
  - 2 LCMV beamformers (pre- and post-stimulus covariance matrices)
- **Resolution Metrics**:
  - Peak Localisation Error
  - Spatial Deviation (extent)

Hauk, Stenroos, Treder, Neuroimage 2022
https://www.sciencedirect.com/science/article/pii/S1053811922002993

Example PSFs and CTFs for MNE and eLORETA

Note: For MNE PSFs and CTFs are the same



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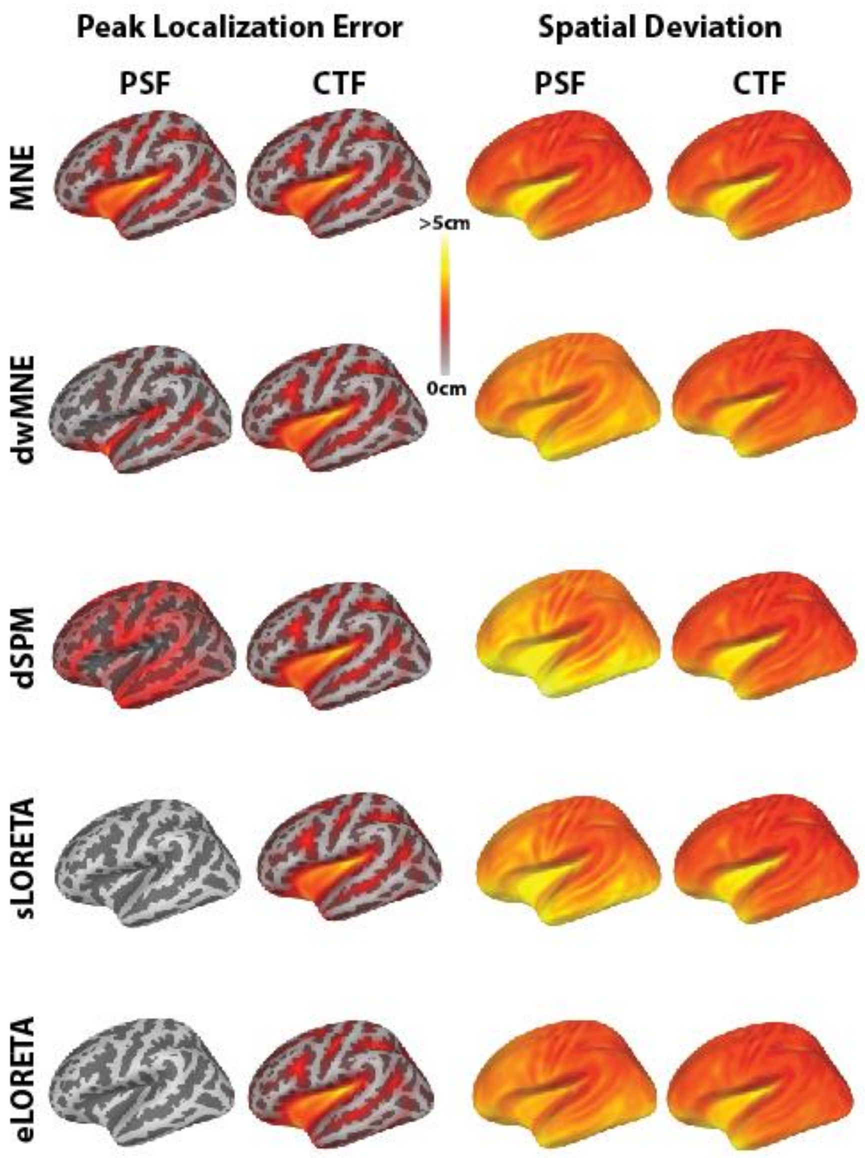
Comparing Estimators – MNE-type



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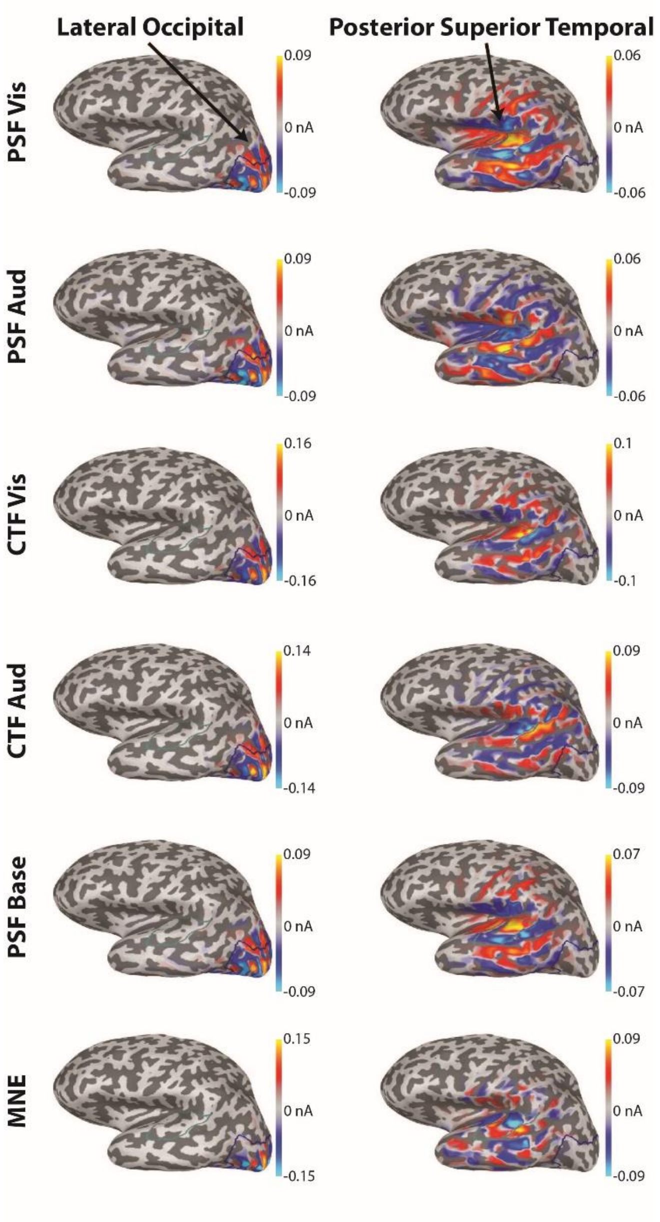
Example PSFs and CTFs for Beamformers



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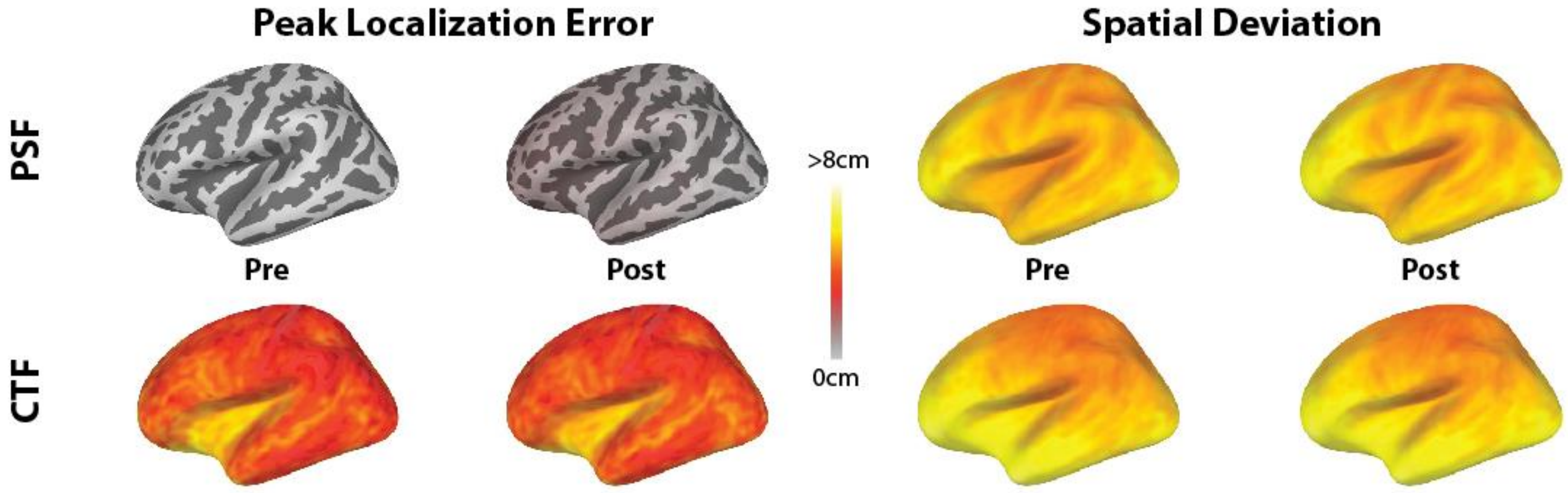
Comparing Estimators – Beamformers



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Conclusion From Methods Comparison

- Methods vary with respect to localisation error and spatial deviation.
- Improvements in localization error are accompanied by increases in spatial deviation.
- Localisation error for PSFs can be minimised (even to zero), but not for CTFs.
- Spatial deviation for PSFs and CTFs cannot be minimised beyond a certain limit.
- Localisation error for beamformers is low (even zero), but spatial deviation higher than for MNE-type methods.
- Performance of beamformers similar for different covariance matrices.

$\Rightarrow$ There is no obvious “best method”.

$\Rightarrow$ In this analysis, MNE and eLORETA seem to offer the best compromise between localisation and spatial deviation.

$\Rightarrow$ The tools (PSFs/CTFs, resolution metrics) can be applied to individual datasets – try it yourself!

Thank you