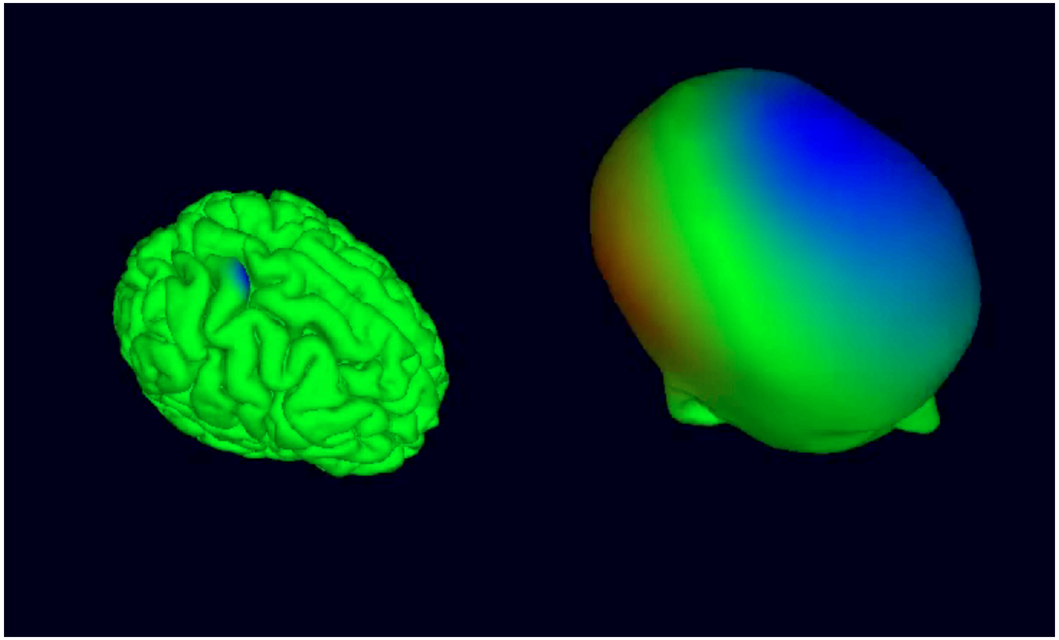


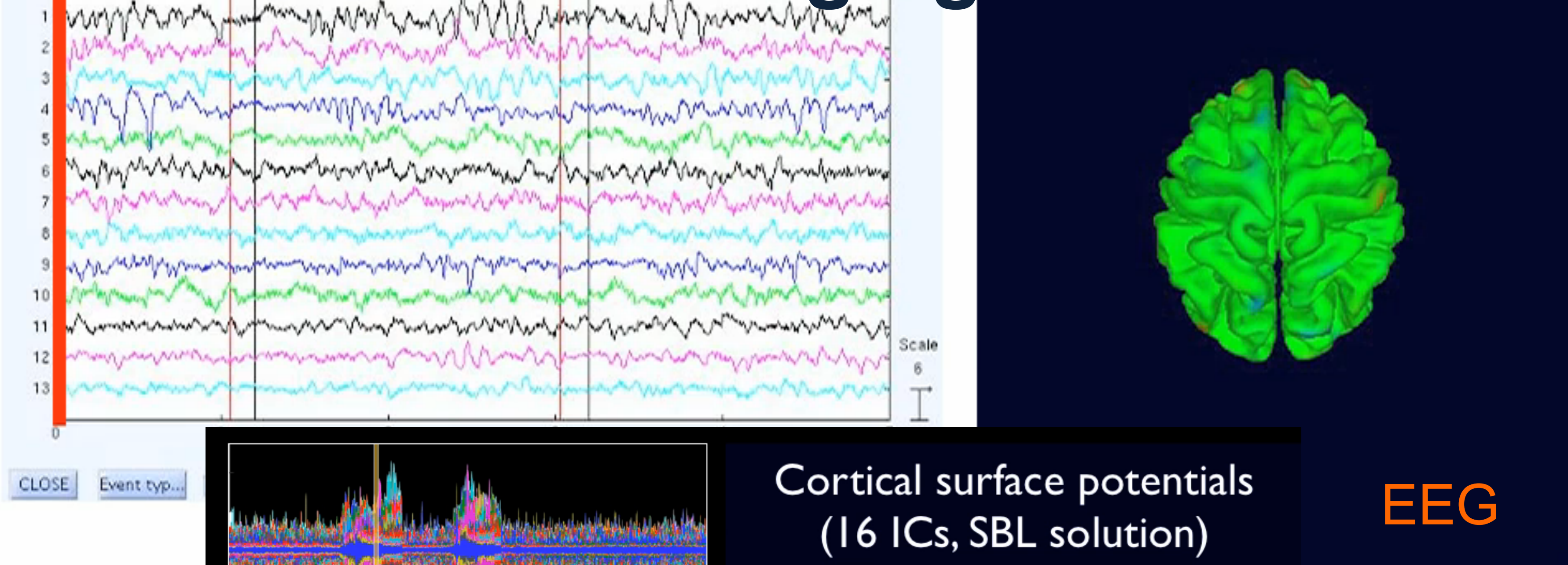
High-resolution EEG source imaging

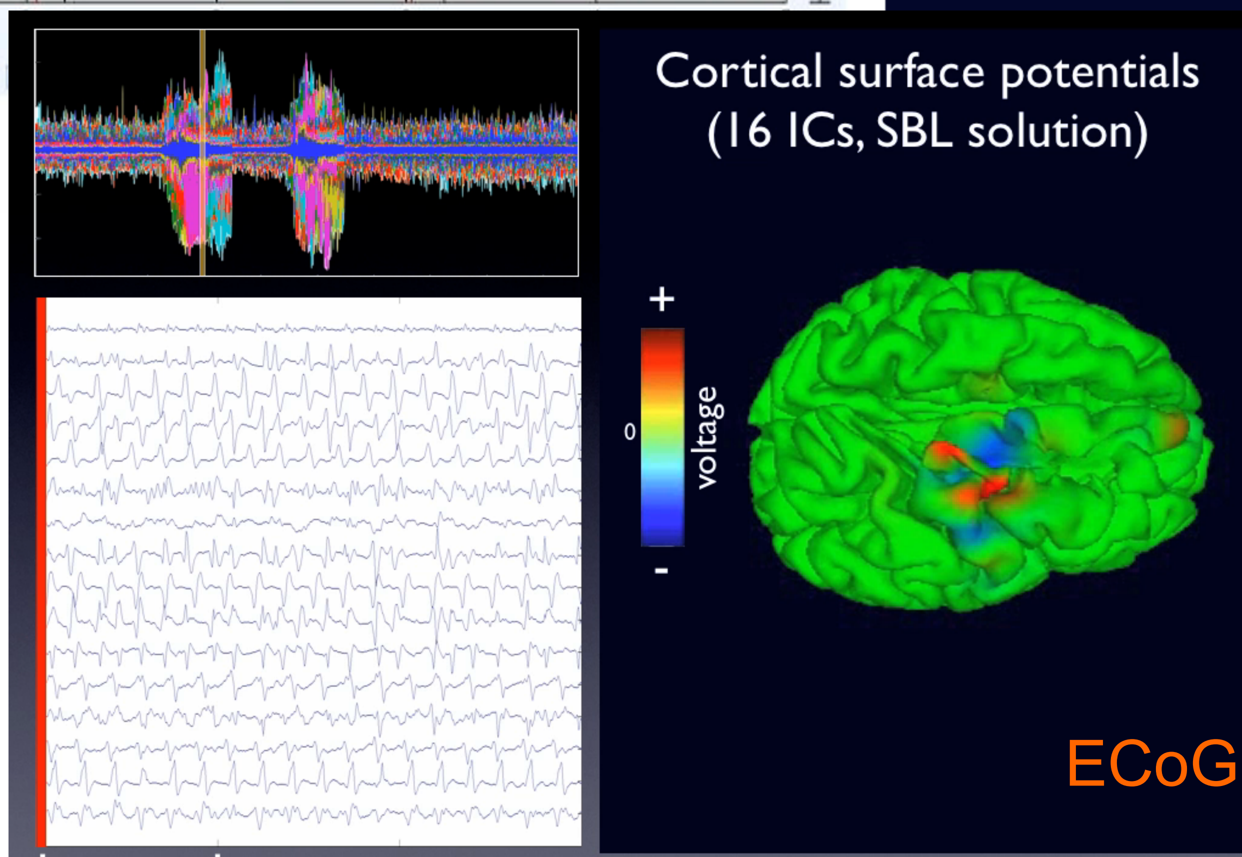
Zeynep AKALIN ACAR

Swartz Center for Computational Neuroscience

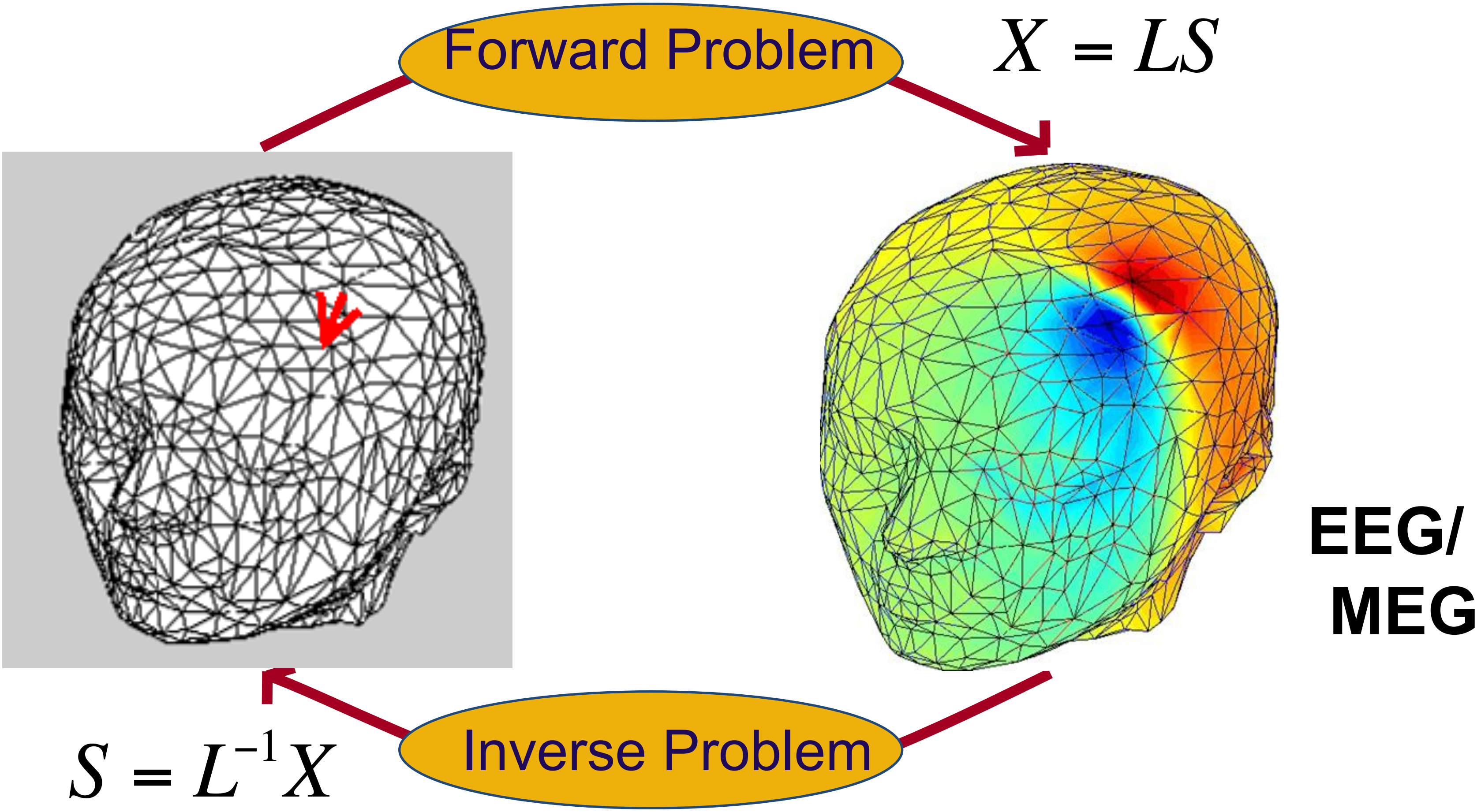
Tokyo institute of Technology, September, 2016

EEG brain source imaging





Source localization problem



= 1000s of FP solution

Source localization is ill-posed

$$X = LS + n$$

X: scalp recorded potentials
S: current density vector
L: transfer matrix ‘the head volume conductor model’

The inverse problem refers to finding S given known X.

$$O(S) = \min \|X - LS\|^2$$

Infinite solutions!

Apply electrophysiological neuroanatomical constraints

1. The electrical head model used,
2. The inverse solution itself

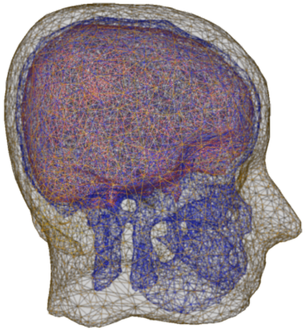
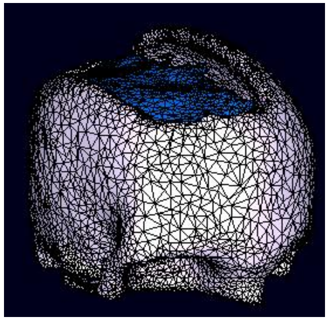
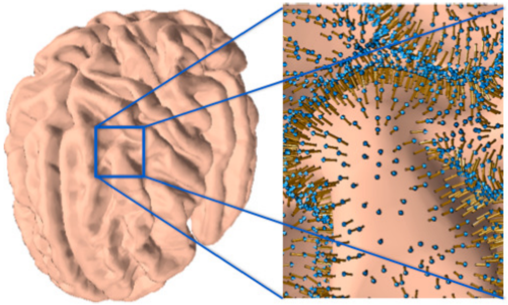
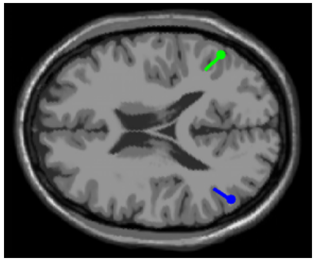
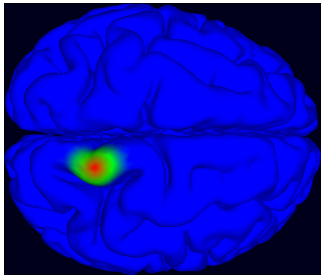
Components of EEG source imaging

NFT

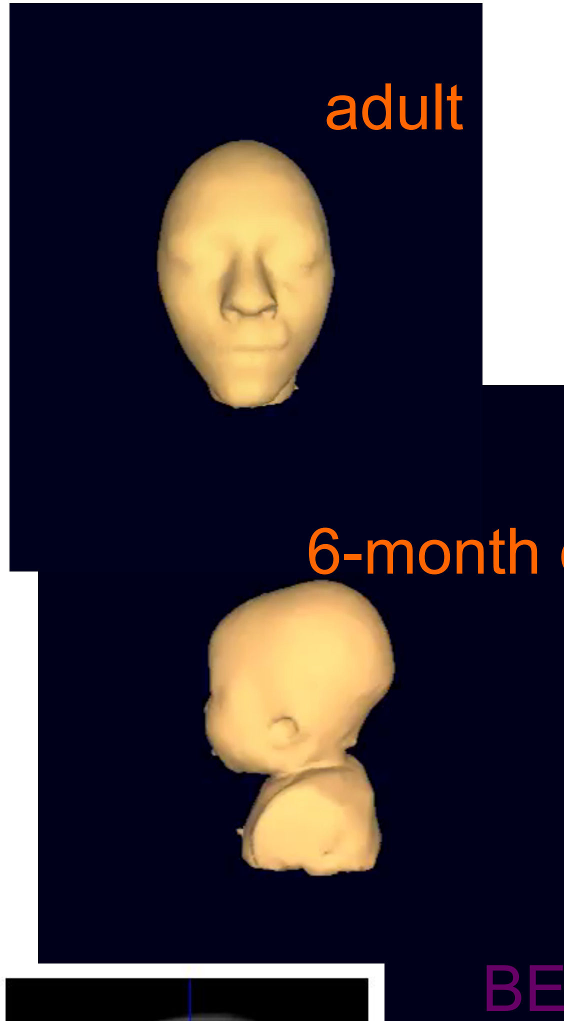
- Forward model (geometry and conductivity distribution)
- Forward solver (FEM, BEM)
- Electrode co-registration
- EEG source separation

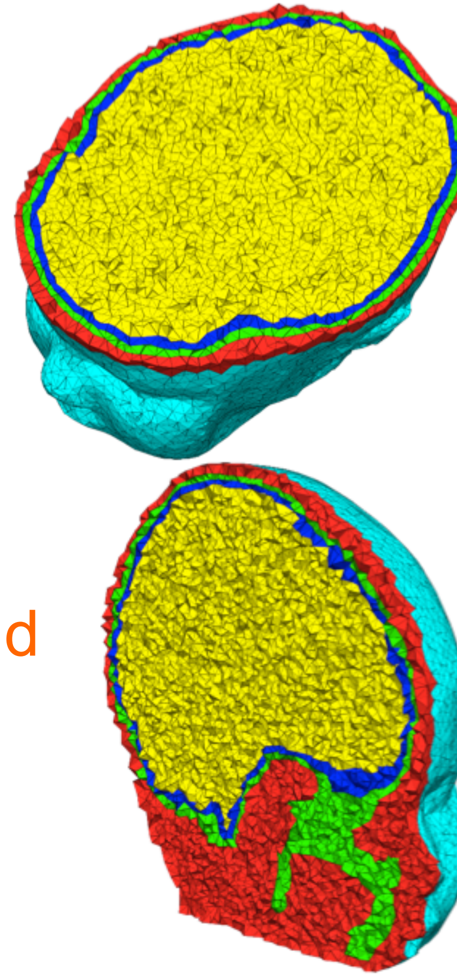
NIST

- Brain source space
- Source localization

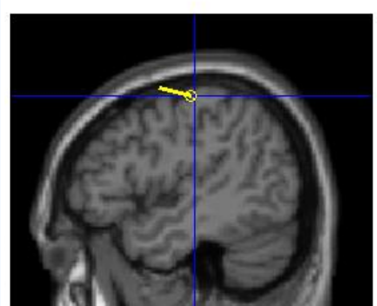
NFT





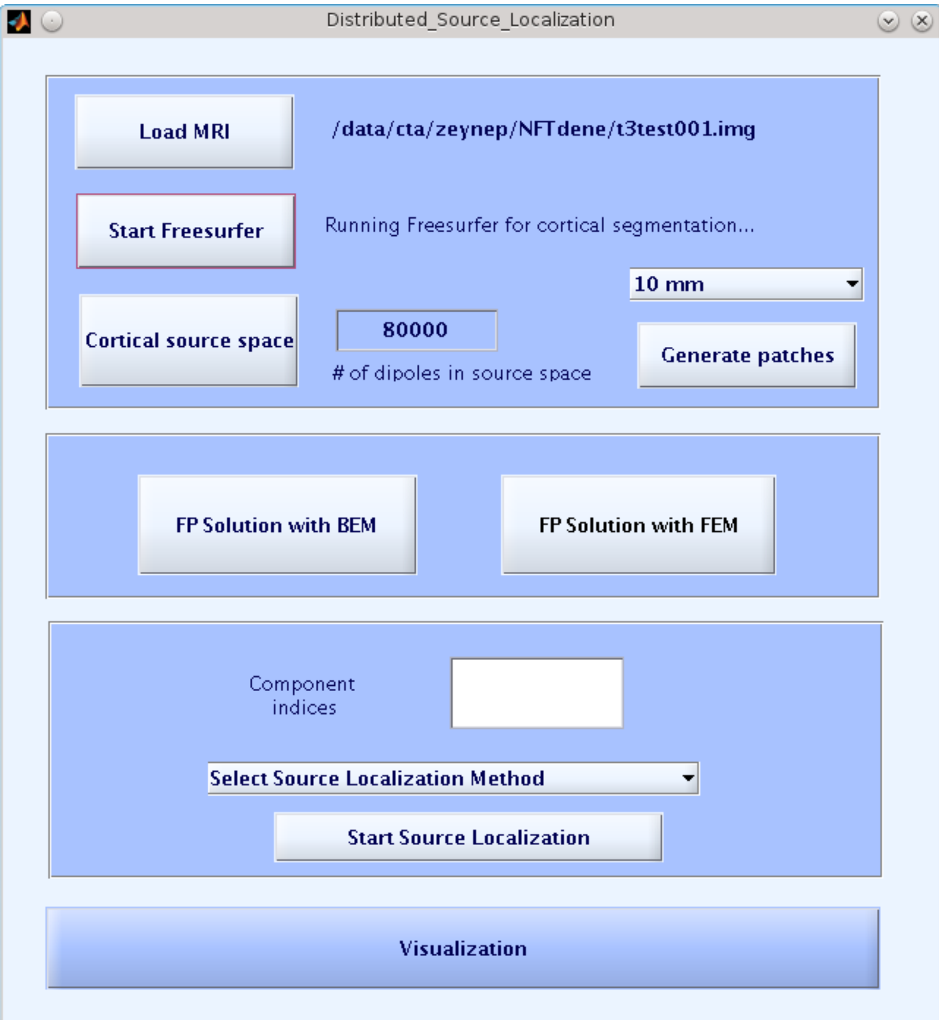
FEM models

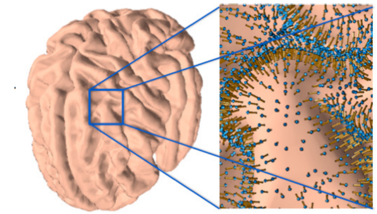
BEM models



Akalin Acar & Makeig, 2010

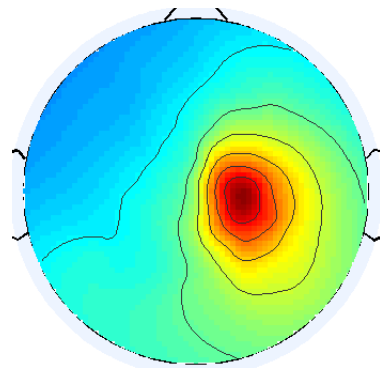
NIST



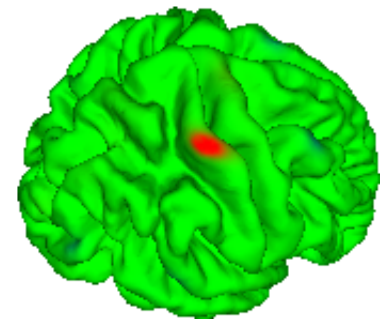


Source space

Scalp map

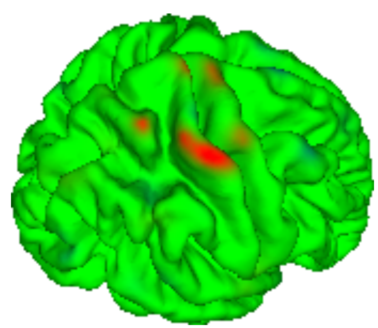


SCS

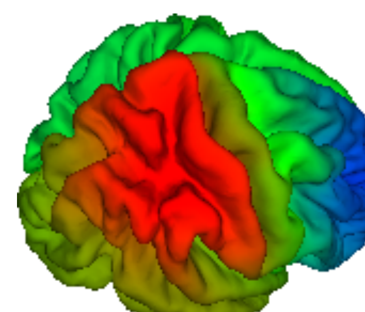


Cheng Cao, 2012

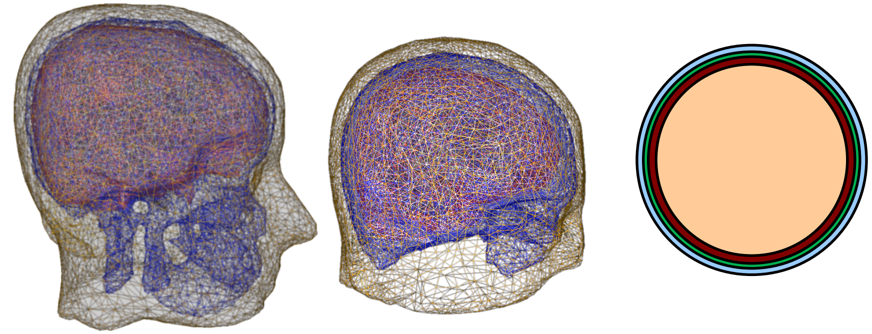
Patch-based SBL



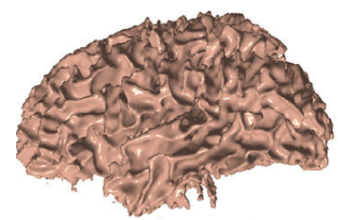
sLORETA



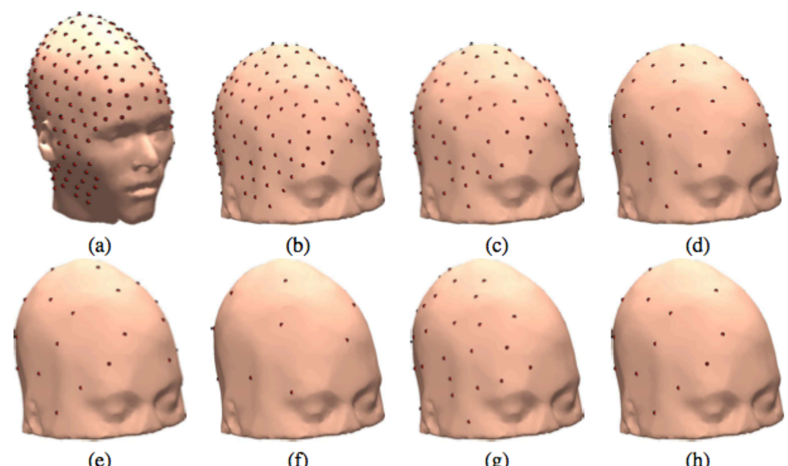
Forward Problem Modeling Errors



- Head modeling errors
- Electrode co-registration errors
- Omitting white matter layer

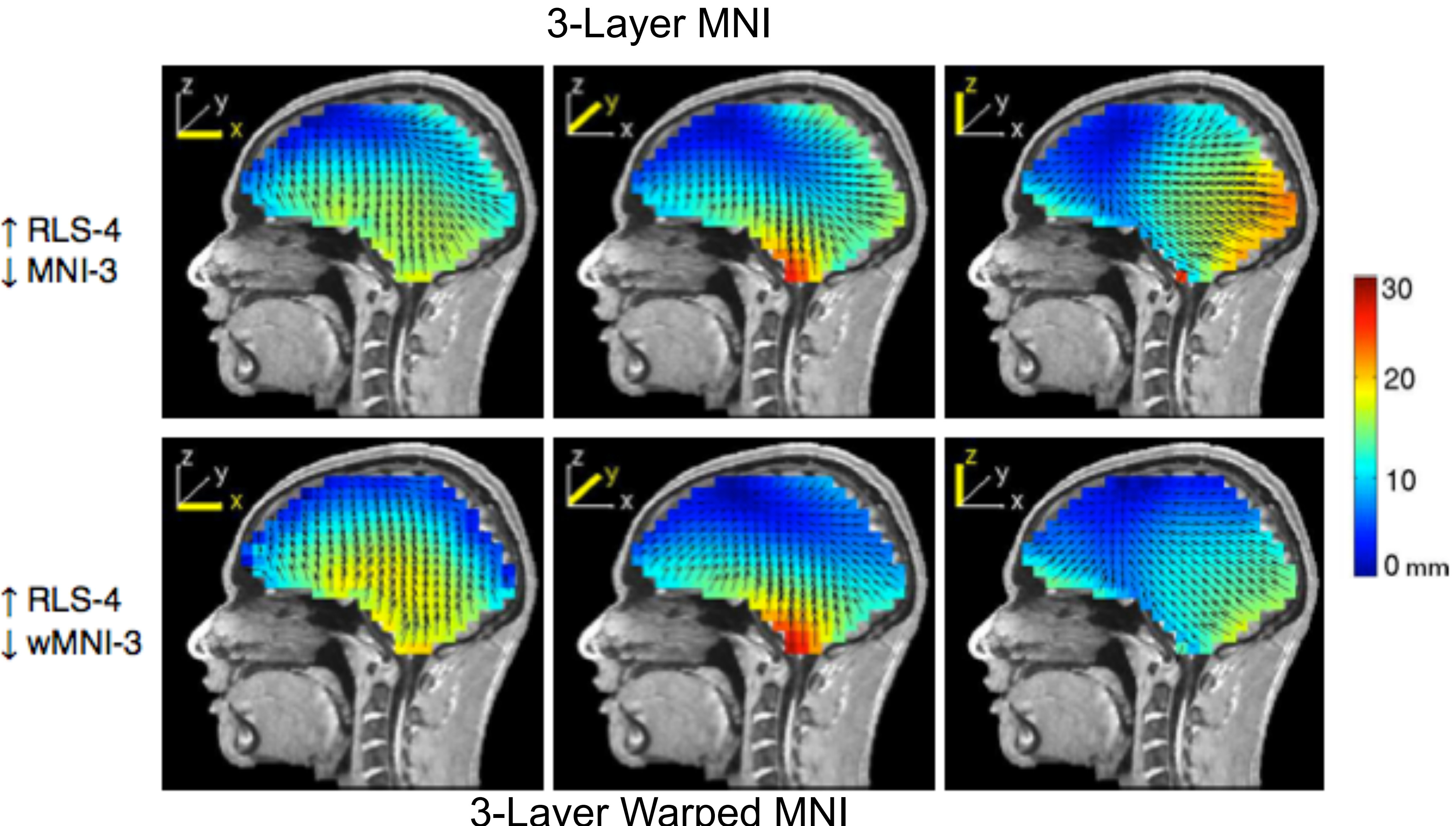


- Effect of skull conductivity
- Number and distribution of electrodes

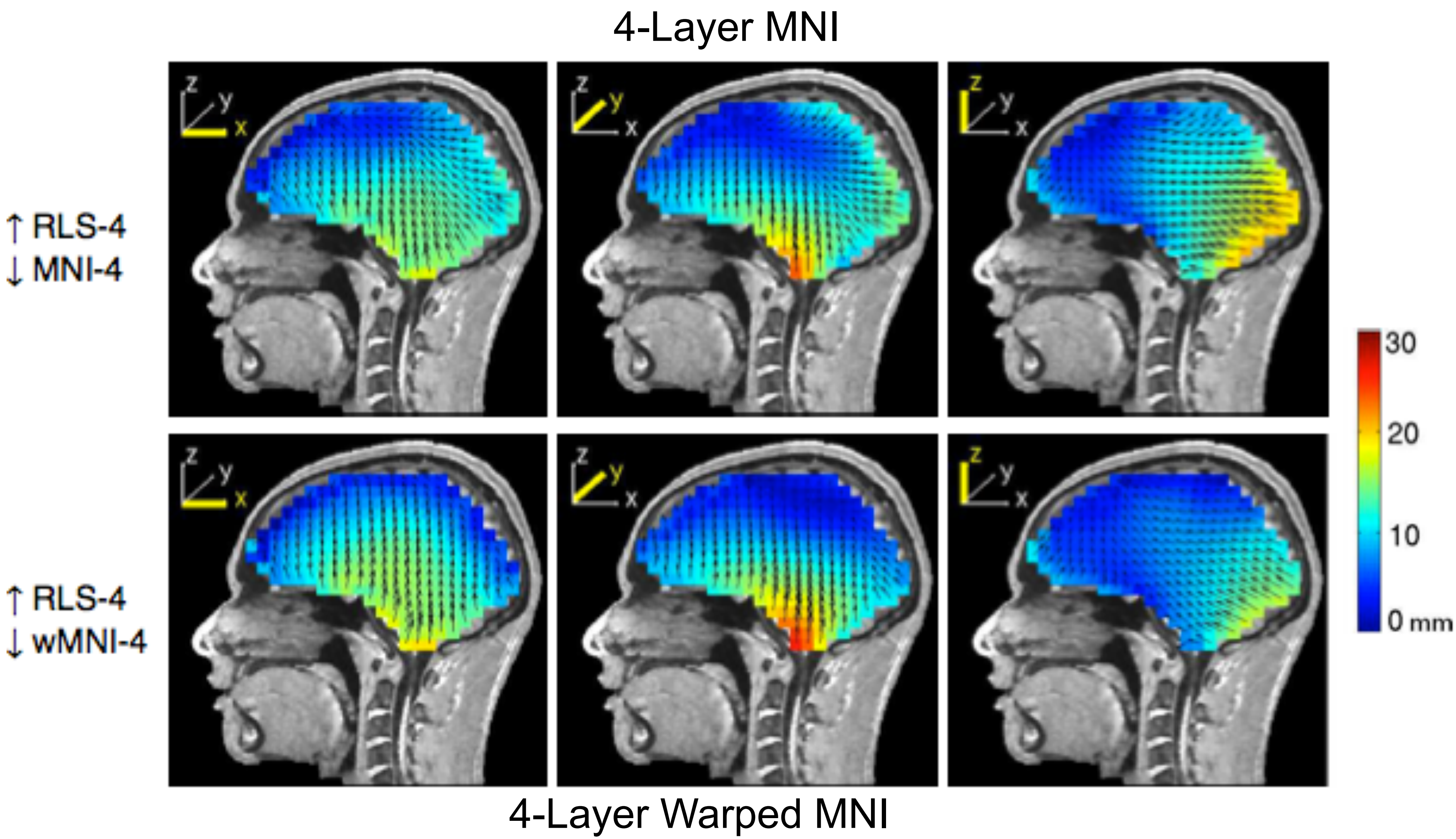


Akalin Acar & Makeig, 2013

3-Layer MNI Location Errors



4-Layer MNI Location Errors

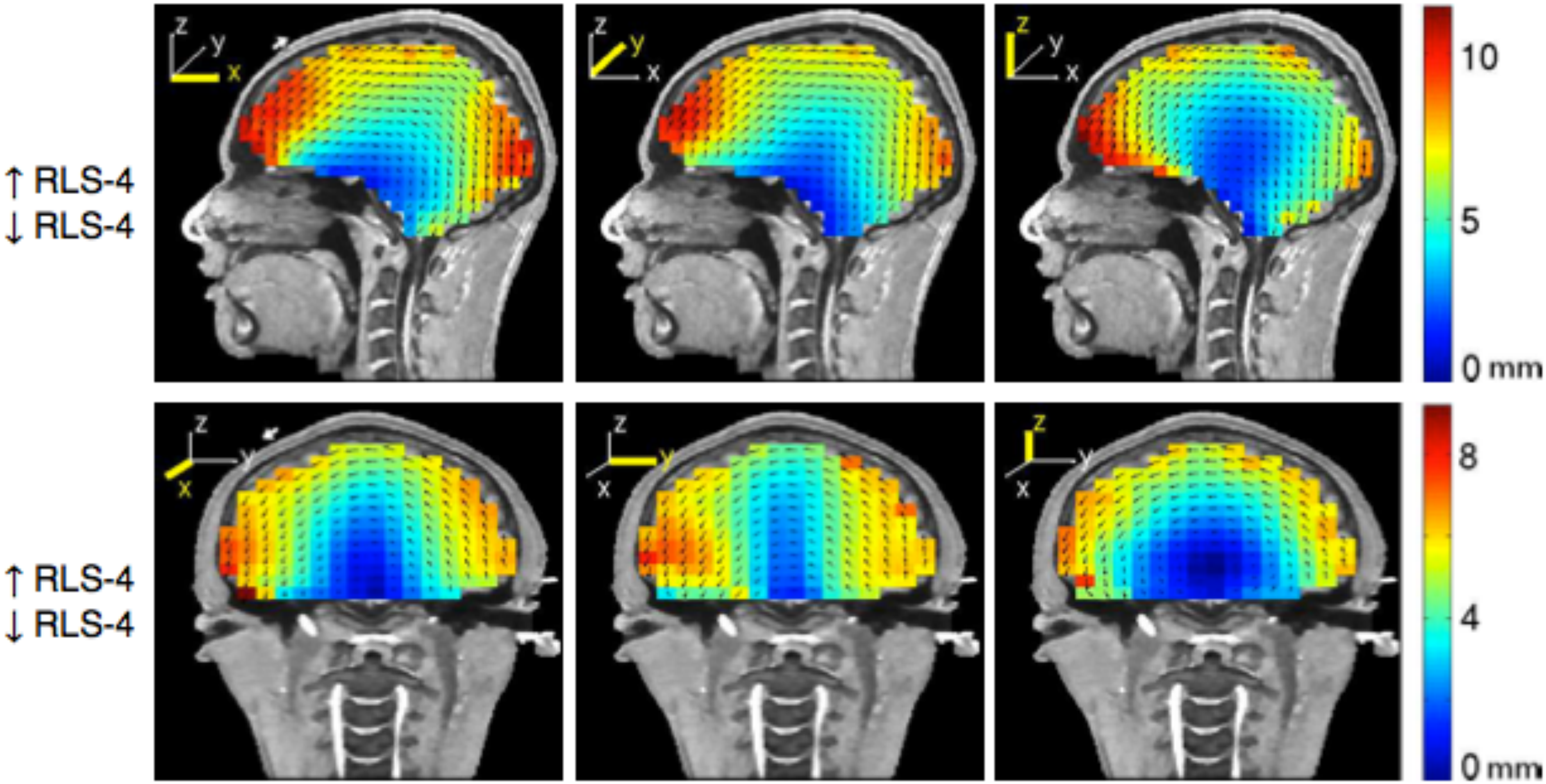


Akalin Acar and Makeig, 2013

Electrode co-registration errors

- Solve FP with reference model
- Shift all electrodes and re-register
  - 5° backwards
  - 5° left
- Localize using shifted electrodes
- Plot location and orientation errors

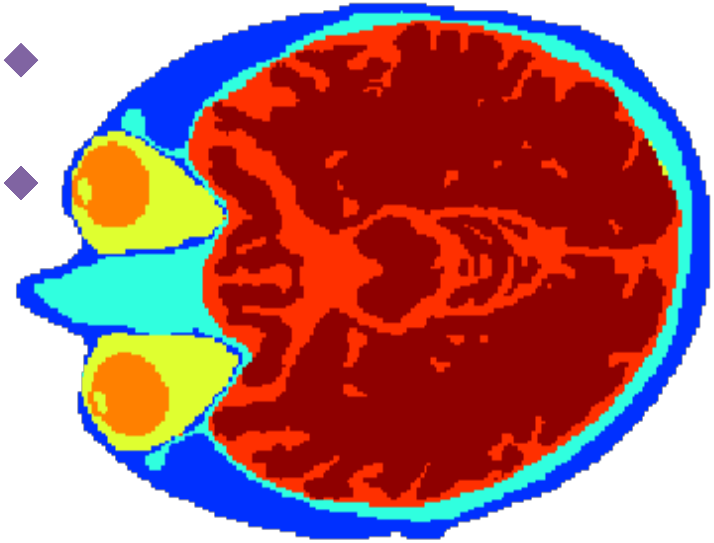
Location Errors with 5° electrode shift



Akalin Acar and Makeig, 2013

Head tissue conductivities

- Scalp : 0.33 S/m
- Skull: 0.0042 S/m (0.08-0.0073 S/m)
- CSF: 1.79 S/m
- Brain: 0.33 S/m

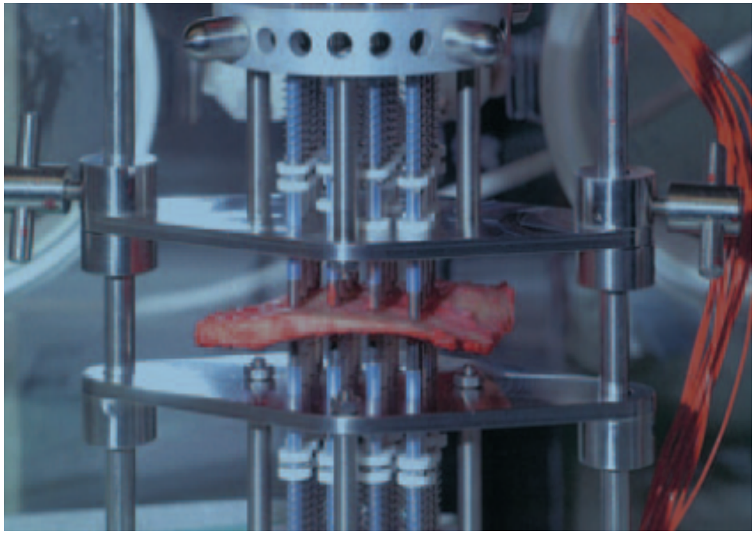


Skull conductivity measurement

Measurement of skull conductivity

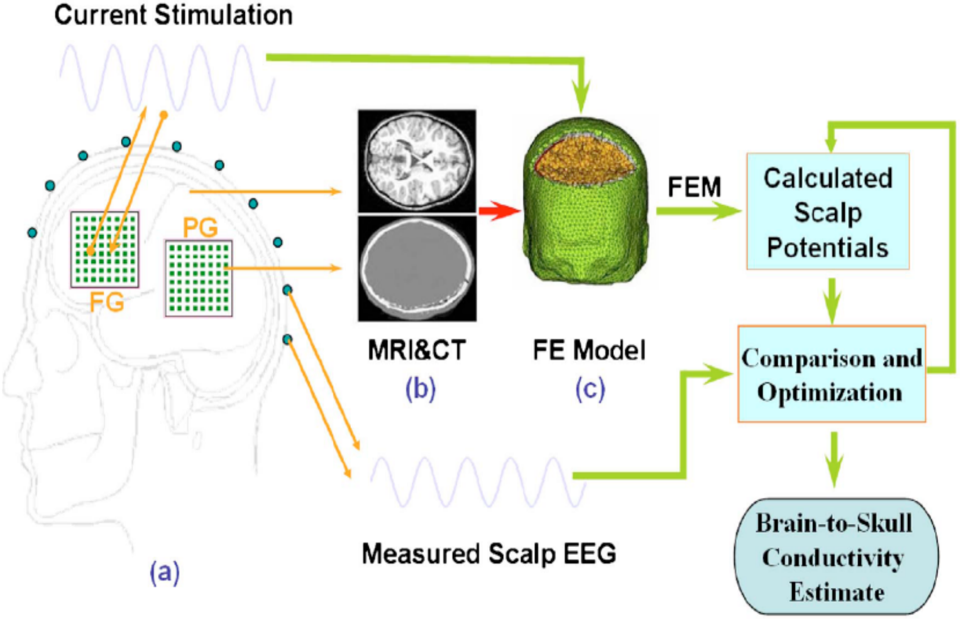
MREIT
Magnetic stimulation
Current injection

In vivo



Hoekama *et al*, 2003

In vitro



He *et al*, 2005

Skull conductivity

Brain to skull ratio		
Rush and Driscoll	1968	80
Cohen and Cuffin	1983	80
Oostendorp et al	2000	15
Lai et al	2005	25

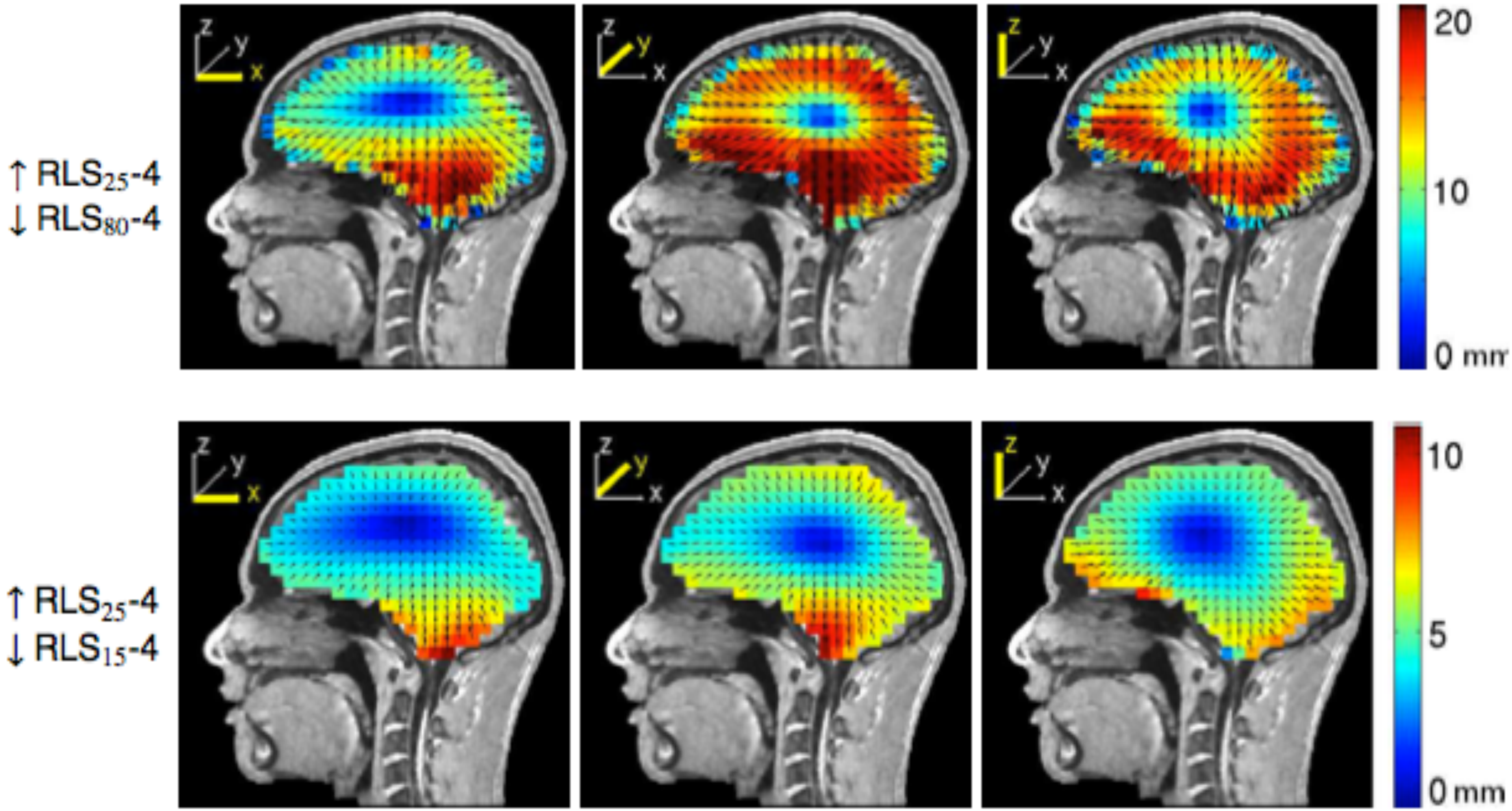
Measurement	Age	σ (mS/m)	ratio
Agar-agar phantom	–	43.6	7.5
Patient 1	11	80.1	4
Patient 2	25	71.2	4.6
Patient 3	36	53.7	6.2
Patient 4	46	34.4	9.7
Patient 5	50	32.0	10.3
Post mortem skull	68	21.4	15.7

Hoekam

Effect of Skull Conductivity

- Solve FP with reference model
  - Brain-to-Skull ratio: 25
- Generate test models
  - Same geometry
  - Brain-to-Skull ratio: 80 and 15
- Localize using test model
- Plot location and orientation errors

Skull conductivity mis-estimation



Akalin Acar and Makeig, 2013

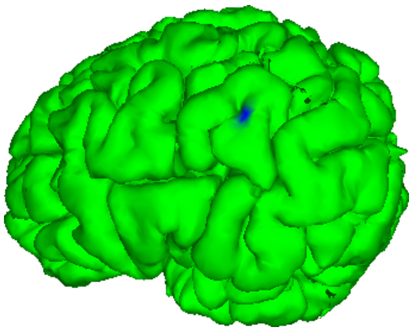
Skull conductivity estimation

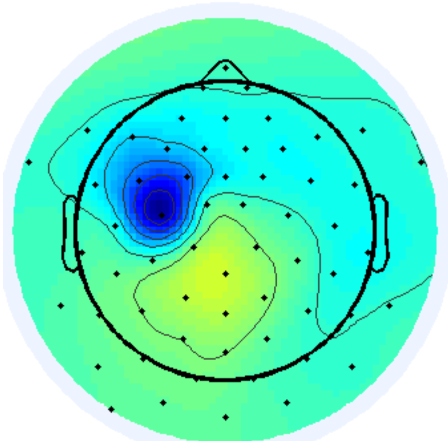
- We propose a skull conductivity estimation method using independent EEG brain sources.
- Patch-based source localization measures:

  - Source compactness

  - Source projection

    goodness of fit





- Linearize the forward problem around a conductivity distribution.

Linearization of the potentials around a conductivity distribution

If we perturb the conductivity values by $\Delta\sigma$

$$\sigma = \sigma_0 + \Delta\sigma \qquad \Rightarrow \qquad \Phi = \Phi_0 + \Delta\Phi$$

For a discretization with N nodes and M elements:

$$A(\sigma)\Phi = b$$

Φ: Nx1 vector of unknown node potentials
σ: Mx1 vector of layer conductivities
A: sparse, symmetric NxN matrix containing geometry and conductivity information
b: Nx1 primary current density

Linearization of the potentials around a conductivity distribution

Changes in the potentials at the electrode locations:

$$\Delta\Phi_s = -DA(\sigma_0)^{-1} \left.\frac{\delta A(\sigma)}{\delta\sigma}\right|_{(\sigma=\sigma_0)} \Phi_0 \Delta\sigma$$

$$\Delta\Phi_s = S_\Phi \Delta\sigma$$

S: mxM sensitivity matrix

Gencer and Acar, 2004

Iterative procedure

1. Generate a head model - **NFT**
2. Calculate the forward model using initial conductivity distribution - **NFT**
3. Estimate source distribution (for P number of near-dipolar ICA sources) - **NIST**
4. Calculate the sensitivity matrix.
5. Estimate the change in the conductivity values
6. Update the conductivity, repeat 2, 3, 4, and 5.

Conductivity estimation

Estimate the conductivity change by minimizing the topological difference between EEG and calculated potential:

$$\Delta\hat{\sigma}_i = \min_{\Delta\sigma} RDM(\Phi_{EEG}, \Phi_i)$$

Since: $\Phi_i = S_i \Delta\sigma_i + \Phi_{i-1}$

$$\Delta\hat{\sigma}_i = \min_{\Delta\sigma} RDM(\Phi_{EEG}, S_i \Delta\sigma_i + \Phi_i)$$

Weights

$$\overset{\wedge}{\Delta\sigma} = \Delta\sigma w$$ Px1, P: number of sources

1. M1: Weight every source equally: $w_i = 1/P,\ i = 1...P$
2. M2: Weight the estimate source according to the compactness of its estimated source distribution

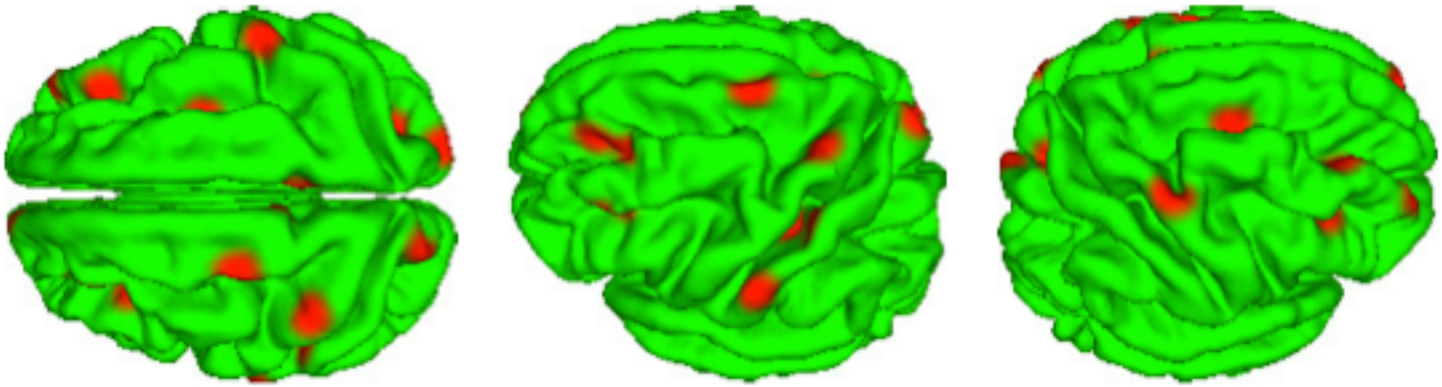
$$w_i = \frac{compactness(i)}{\sum_{j=1}^{P} compactness(j)},\ i = 1...P$$

3. M3: Incorporate both the compactness and the RDM in computing the source weight:

$$w_i = \frac{compactness(i) \times RDM(\Phi_{IC_i}, \Phi_i)}{\sum_{j=1}^{P} compactness(j) \times RDM(\Phi_{IC_j}, \Phi_j)},\ i = 1...P$$

Simulation study

20 cortical Gaussian patch sources used in the simulations.

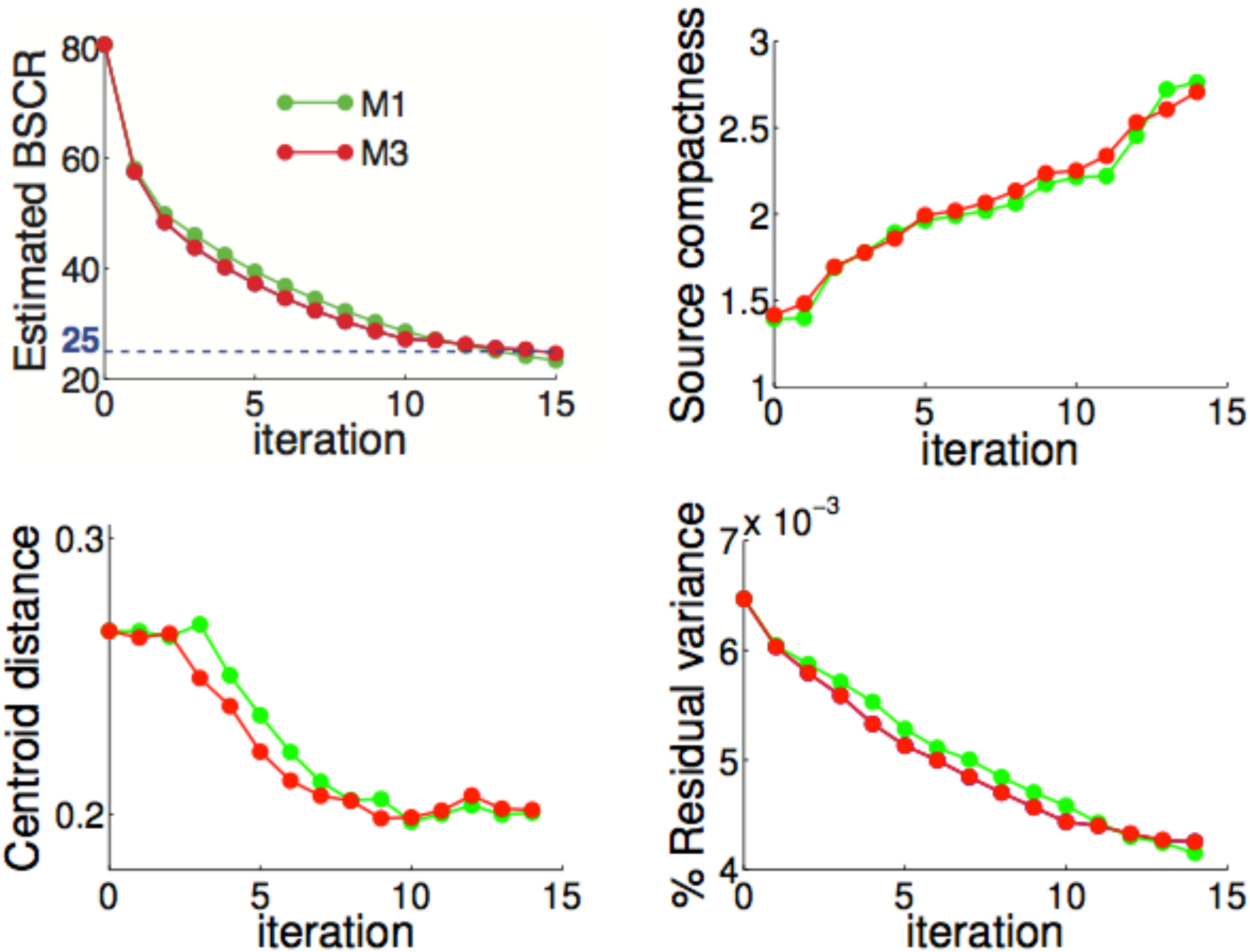


10 mm radius, 3.33 mm std., 128 electrode locations

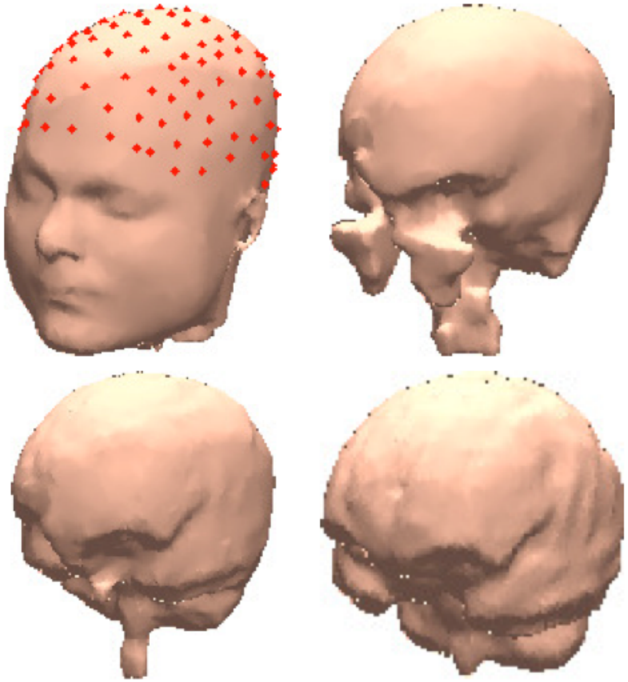
Simulated EEG: BSCR=25

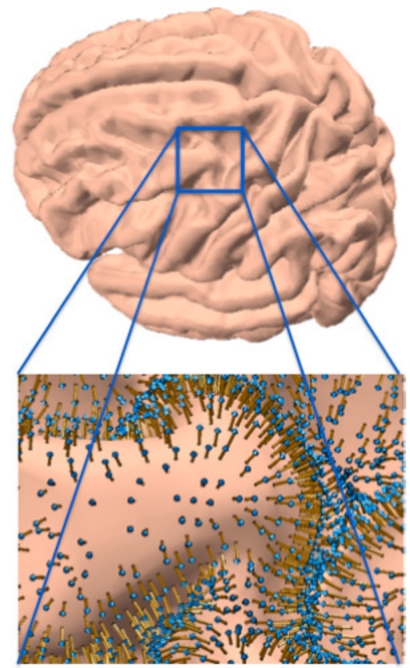
SCALE initialized at BSCR=80.

Simulation results



Real EEG study





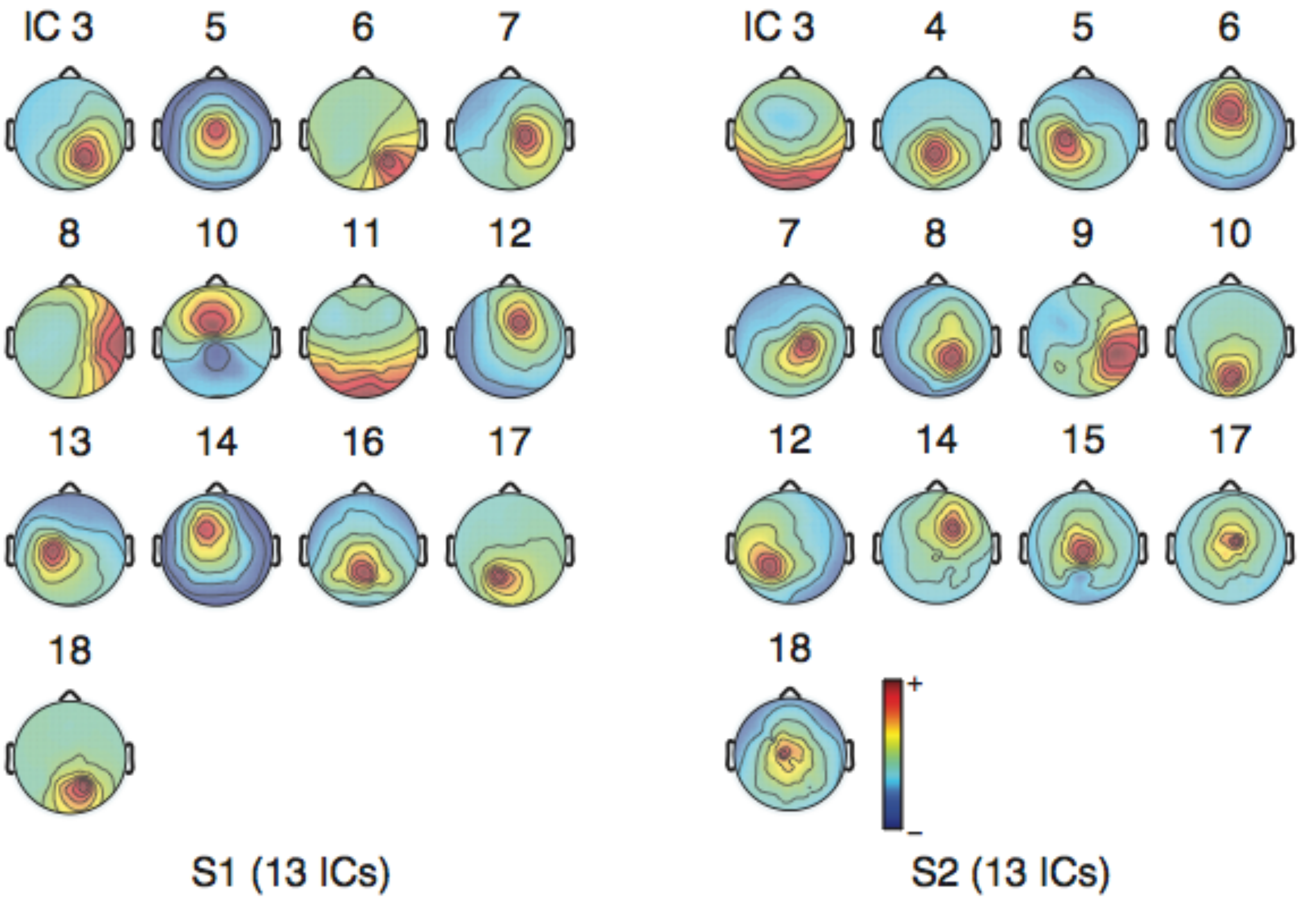
Subjects: 2 male subjects, ages: 20, 23

MRI data: GE 3T whole head MRI with 1 mm^3 resolution.

EEG data: 128 scalp EEG, (256-Hz sampling rate) collected using a Biosemi Active Two system during an arrow flanker task.

Head modeling: NFT is used to generate 4-layer FEM head models. Freesurfer is used to generate cortical source spaces.

Independent Components

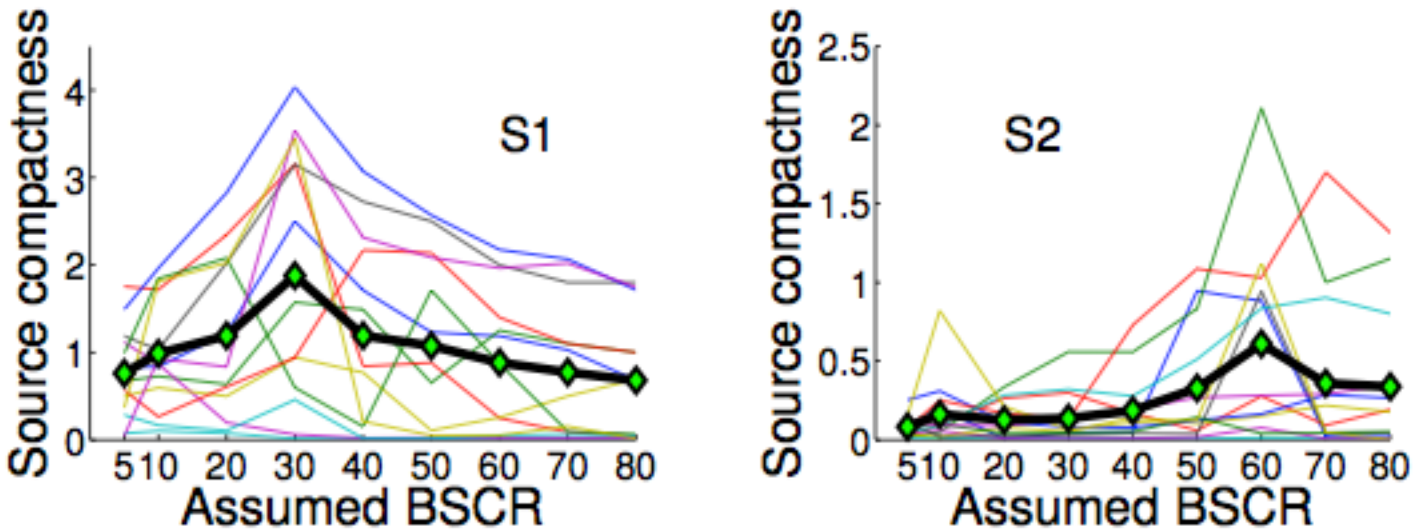


1-model Amica is applied, 13 near-dipolar Ics are selected.

EEG pre-processing: high-pass filter the continuous EEG data above 1 Hz, remove artifacts by initial likelihood-based rejection of time points (5%- 10% of data)

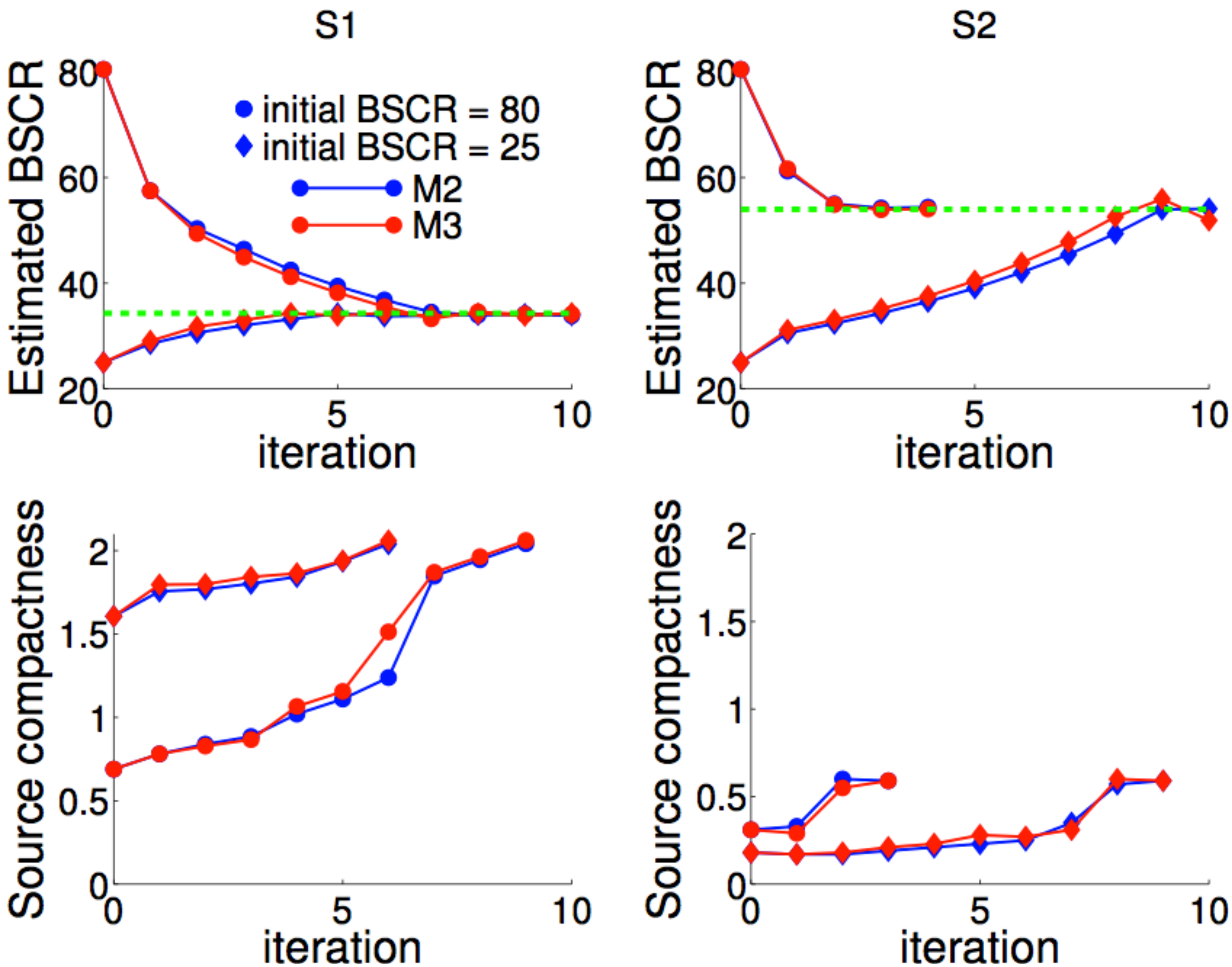
Source Compactness

- Generate 9 electrical forward models with BSCR=5, 10, 20, 30, 40, 50, 60, 70, 80
- Estimate source distributions for the 13 ICs for each subject.
- Compute compactness.

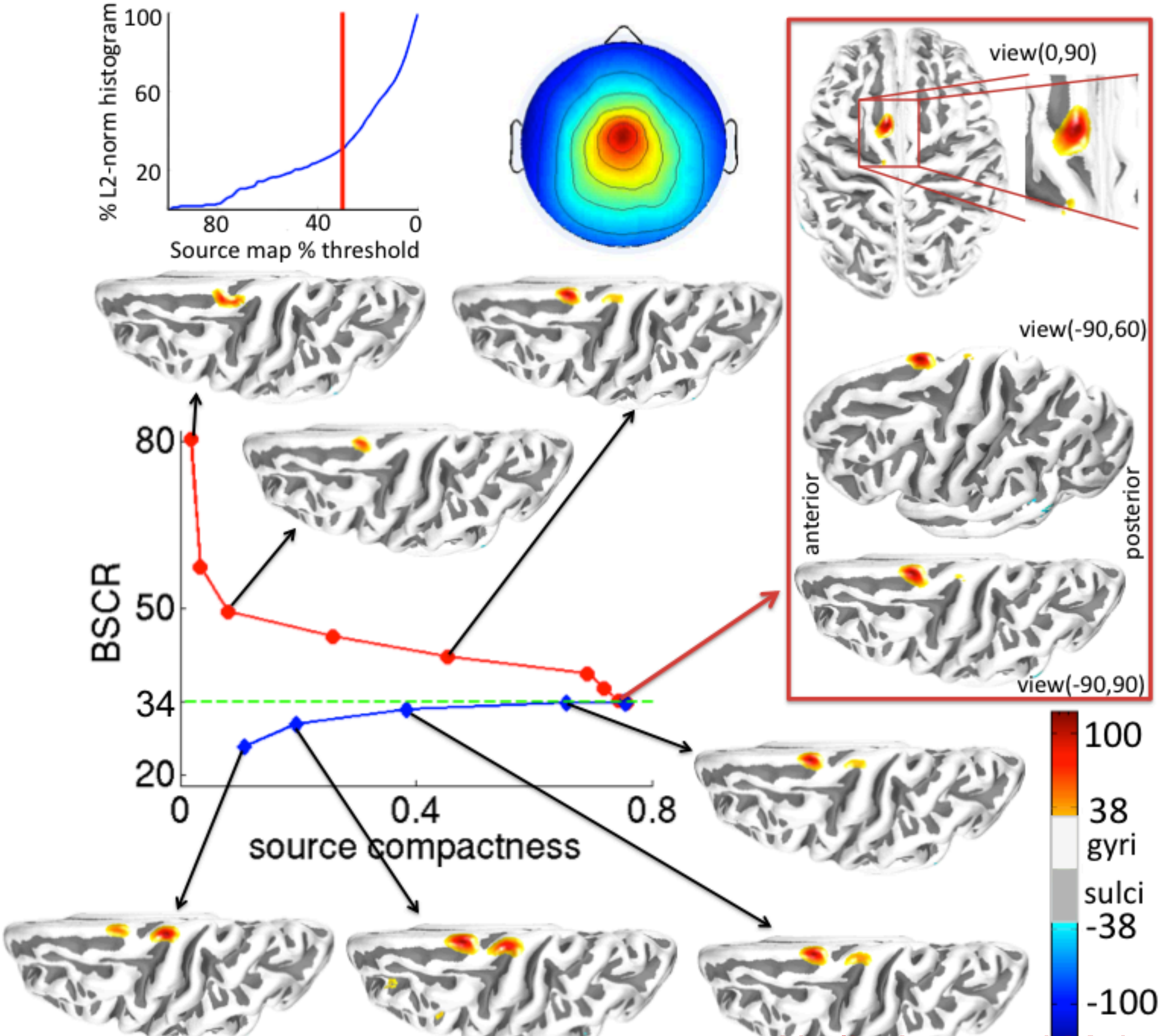


Maximum compactness occurred at BCSR = 30 for S1 and BSCR = 60 for S2.

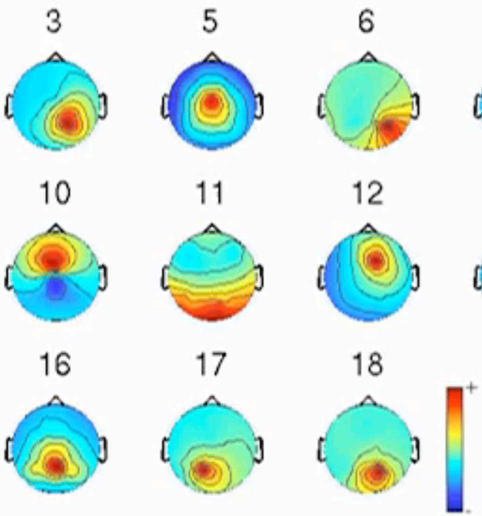
SCALE BSCR convergence

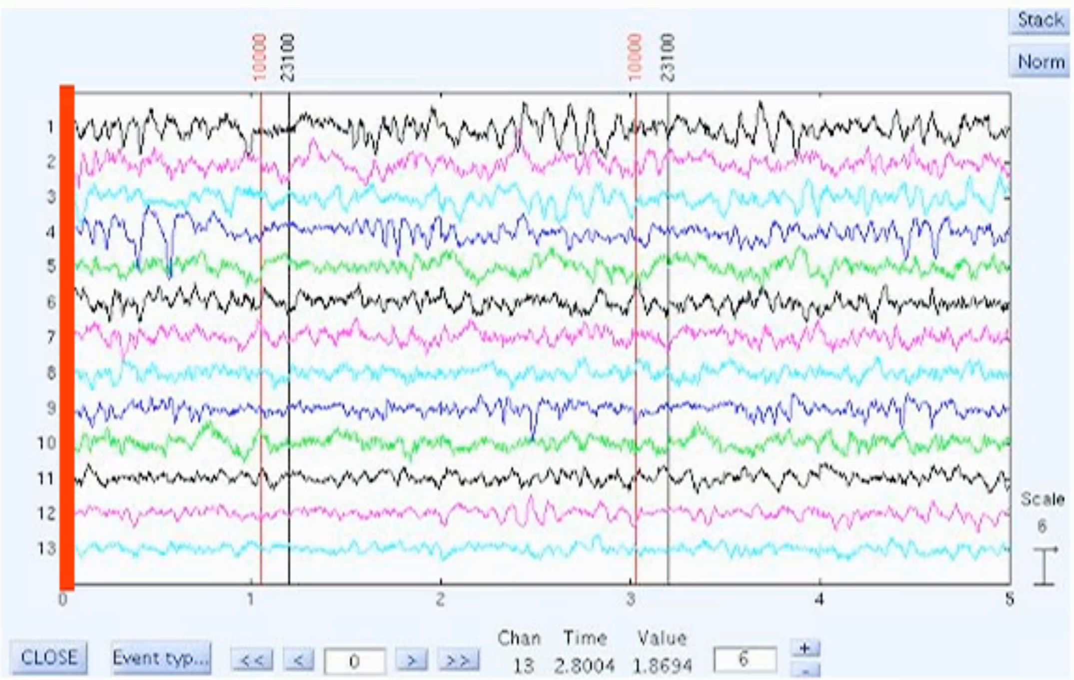


Akalin Acar and Makeig, 2016

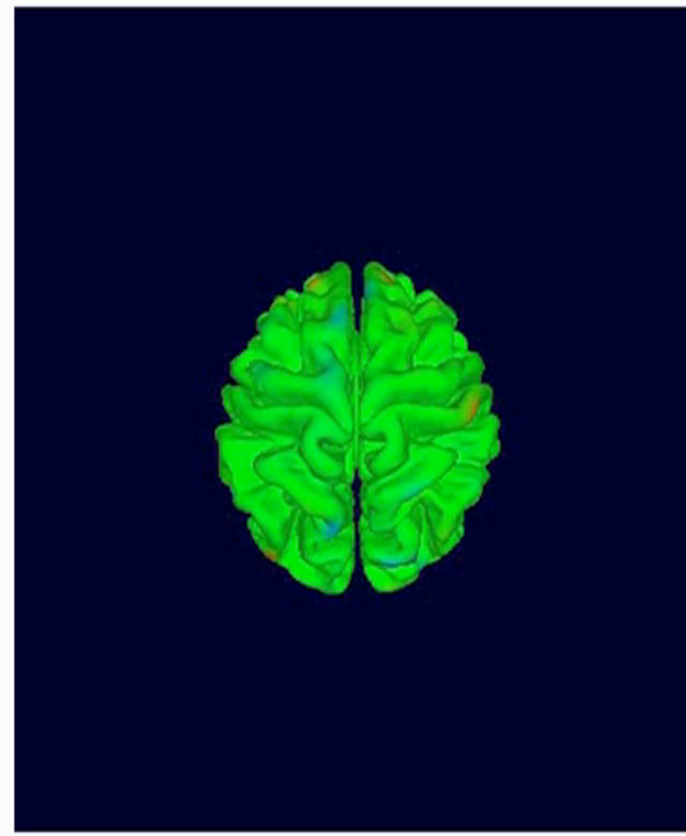


Akalin Acar and Makeig, 2016





13 component activity on the subject's cortical surface



SCALE results

Effect of # of ICs

13 ICs	8 ICs	8 ICs	7 ICs	18 ICs	22 ICs
34	33	21	41	34	34

We need at least 10 ICs with good brain coverage!

	BD	FR	AaV	RB	LH	GV	AS	JH	SE
Strum	28	43	30	68		31	63		31
Darts		45			20				
Arrow Flanker								54	34

SCALE converged to similar BSCR values for the same subjects with different experiments!

Individual baby head models

NFT (sccn.ucsd.edu/nft/) was used to generate four-layer Finite Element (FEM) head models.

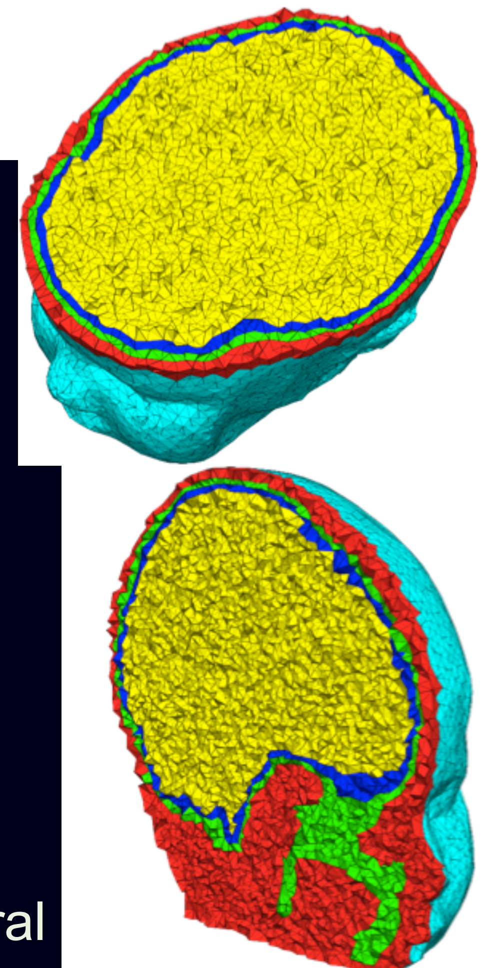
6 months

1,441,777 tetrahedral volume elements

12 months

1,025,643 tetrahedral volume elements

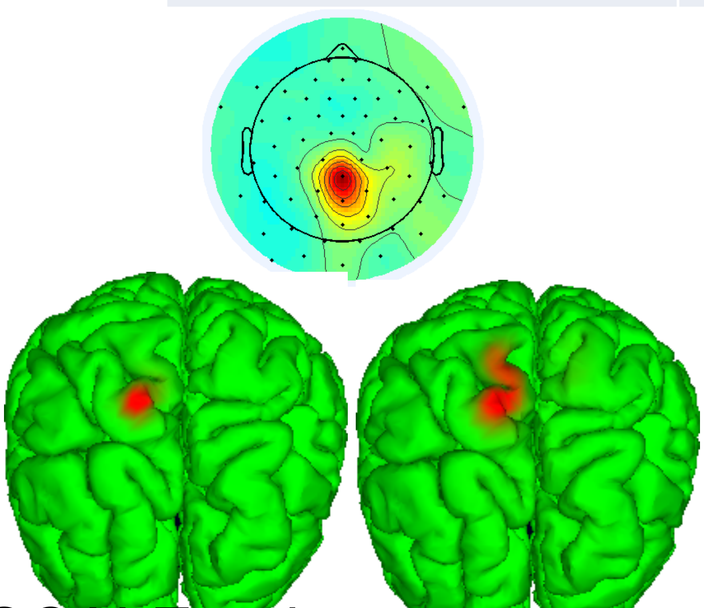
April Benasich data



FEM models

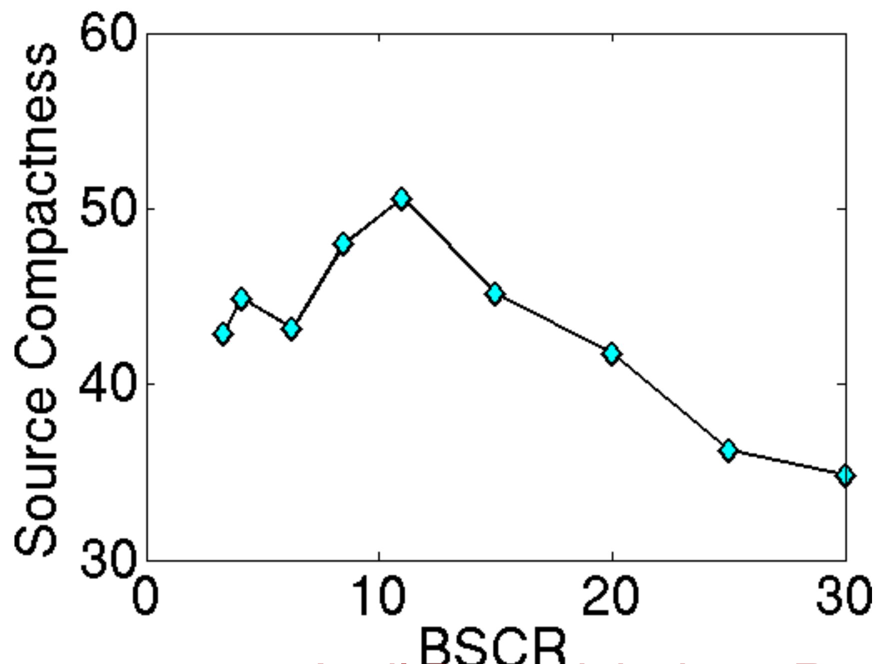
SCALE results of 1-year-old infants

Subjects	Age	# of brain ICs	# of selected ICs	SCALE Ratio
S1	1 year	35	16	9.8
S2	1 year	39	15	10.3
S3	1 year	30	15	12.1
S4	1 year	28	15	10.0



SCALE ratio 9.8

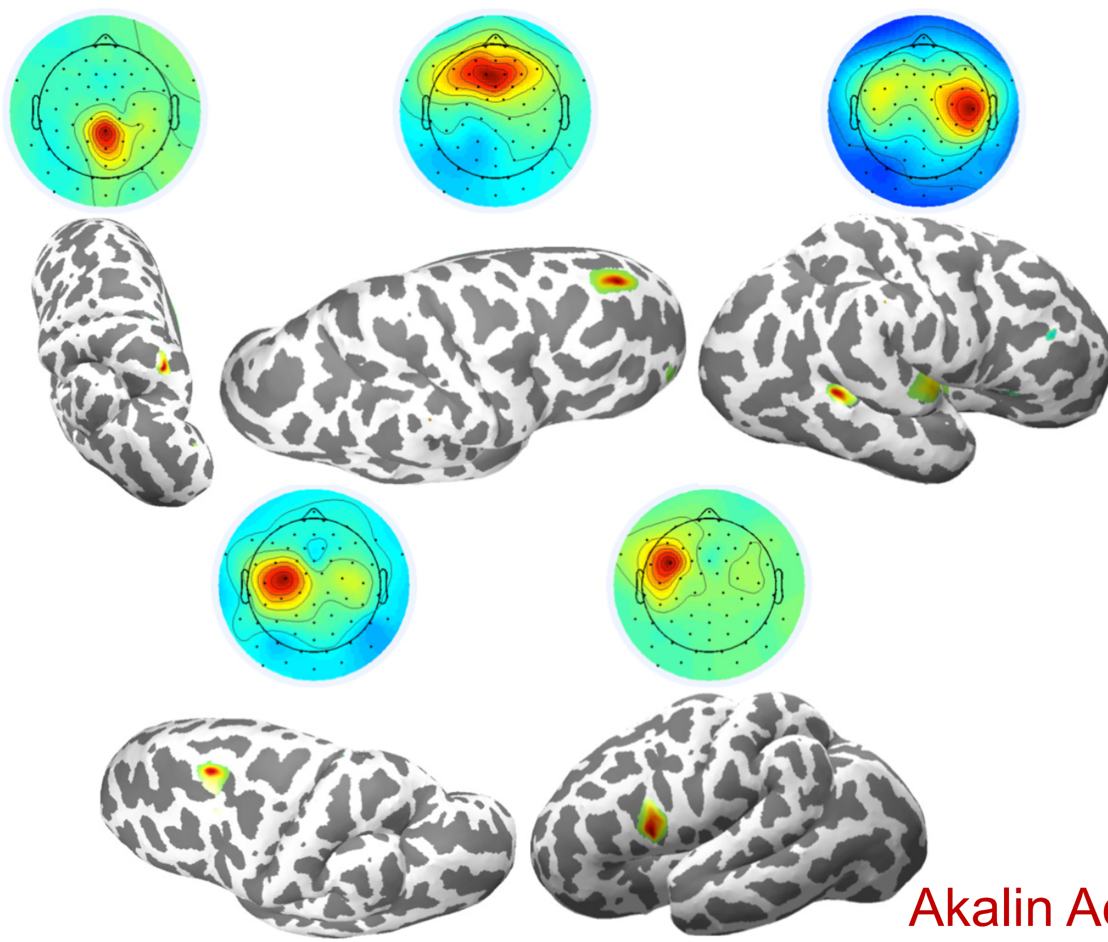
BESA ratio 6.3



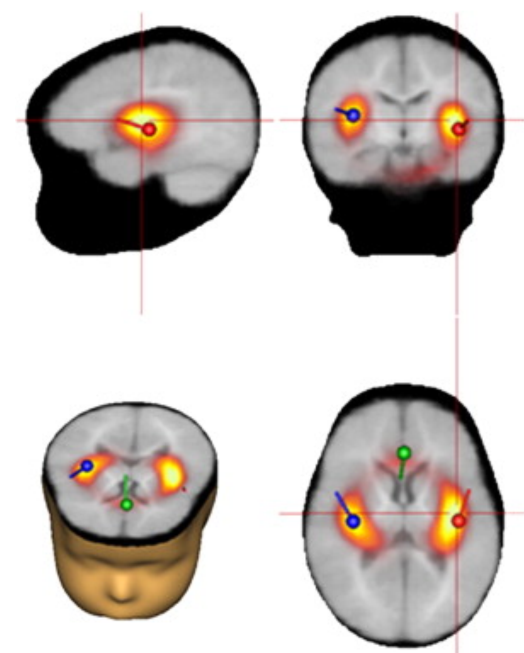
April Benasich data, Rutgers

Source localization results

Source localization results estimated using SCALE, from infants during an auditory experiment.

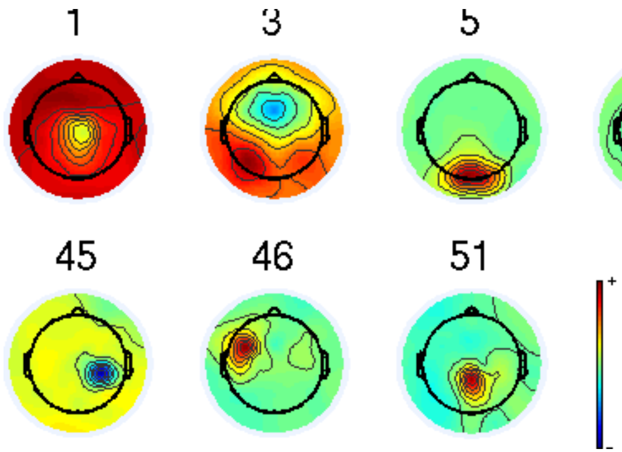


BESA source localization



Hamalainen 2011

Akalin Acar and Makeig, EMBC 2016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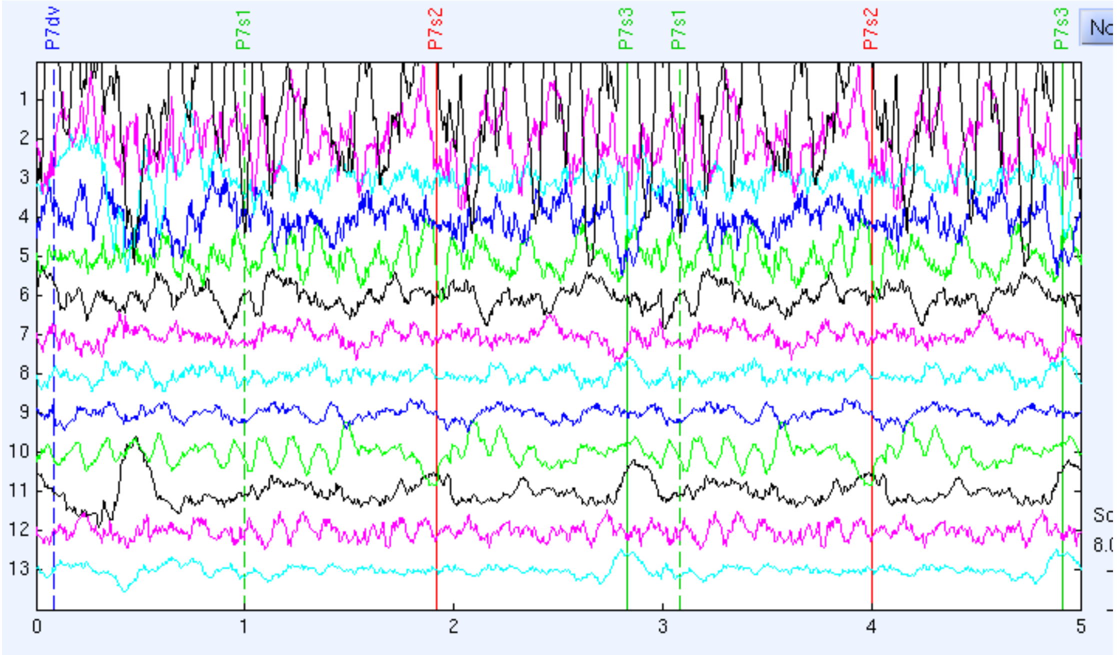
P7dv
P7s1
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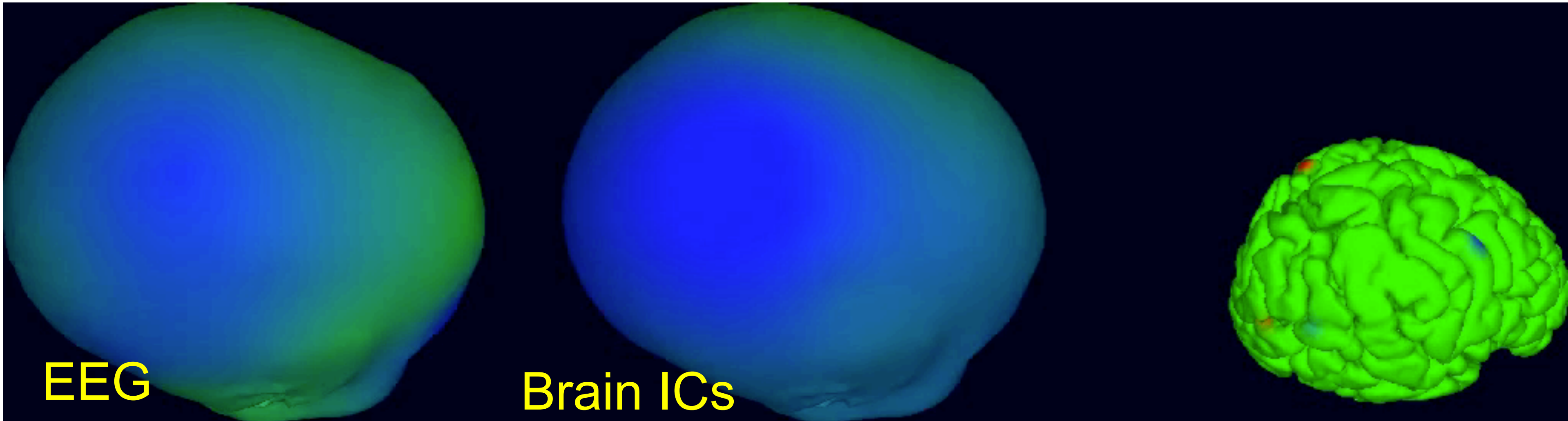
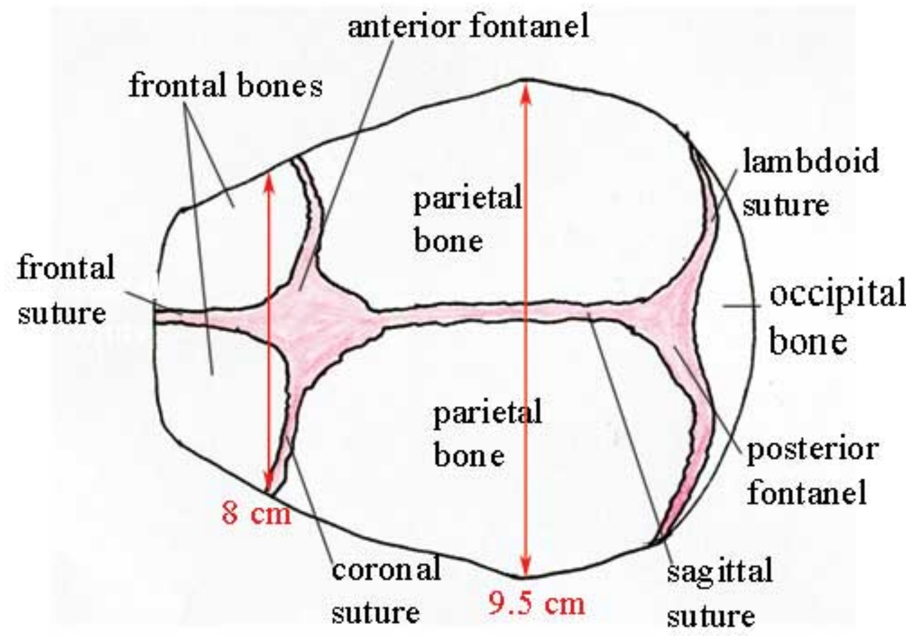

EEG
Brain ICs

Child electrical head modeling challenges



Computational complexity

N: number of nodes in the FEM mesh (~250,000);
L: number of conductivity compartments (1–20);
S: number of brain sources (10–30);
K: number of source dictionary patches (~80,000);
E: the number of scalp electrodes (~128–256).

Steps	Tasks	Computation time
Forward problem setup	Generate FEM matrix (*N x N sparse matrix*)	100-200 MB (20 min)
Forward problem solution	Generate Lead Field Matrix (LFM) (*KxE full matrix*)	80-160 MB (3.7 hours)
Inverse problem	Solve Ax=b (*A: LFM, b: scalp potential Ex1*)	1 hour
Sensitivity matrix	Generate *N x L x S full matrix*	20-1200 MB (6 hours)
Conductivity estimation	Iteratively solve forward, inverse, and sensitivity matrix	10 iterations (4 days)

with N=240,000, K=80,000, E=154, S=13, L=1.

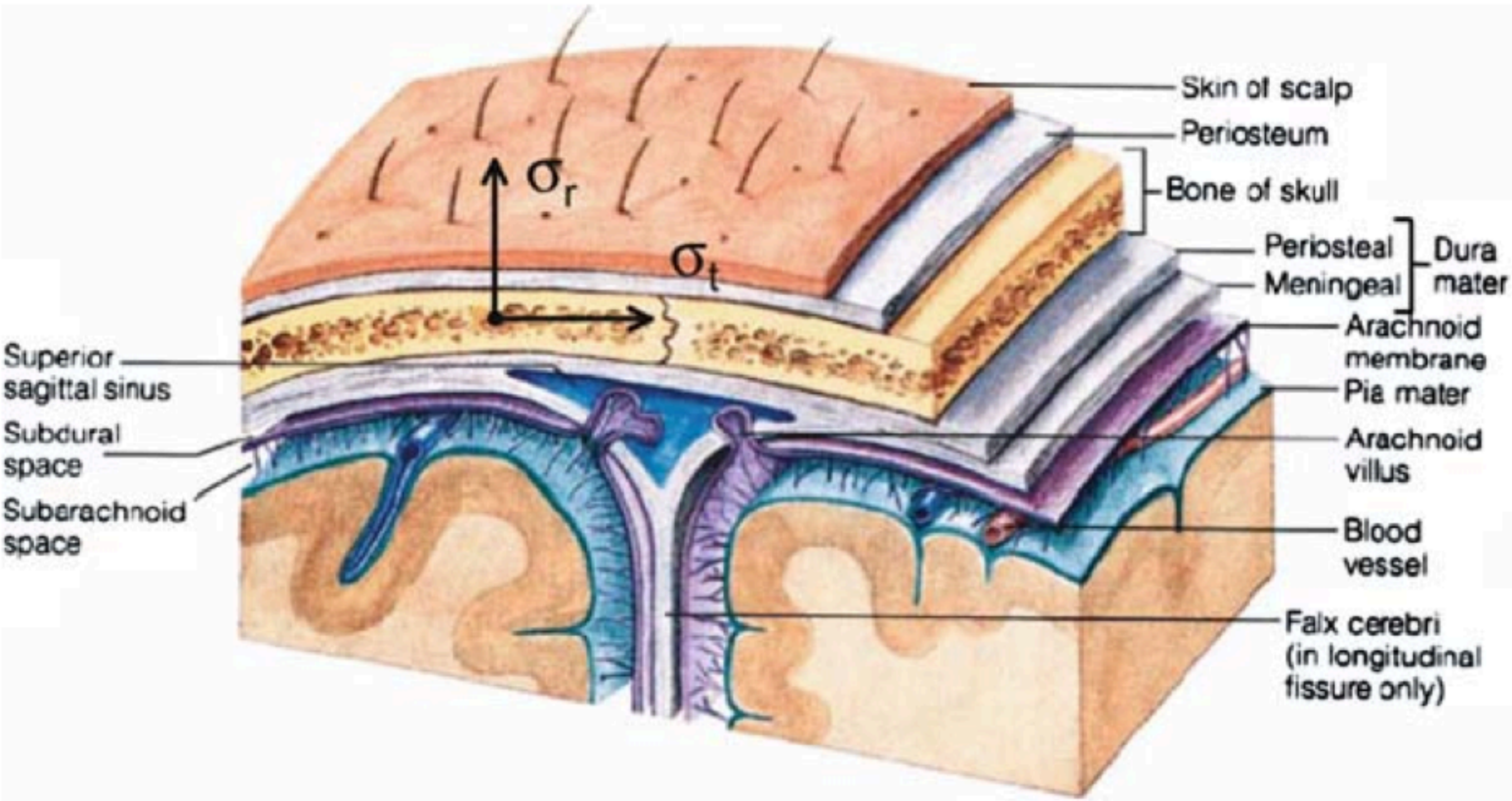
Future work

- Validation of SCALE using simultaneous EEG/MEG data.
- Near real-time implementation of EEG brain activity imaging.
- Generation of template head models based on age and gender when MR images are not available.

Thank you…

Swartz Center for Computational Neuroscience

The 3-layer skull



Skull anisotropy -> Skull inhomogeneity (3-layer skull)

(Sadleir 2007, Dannhauer 2011)